

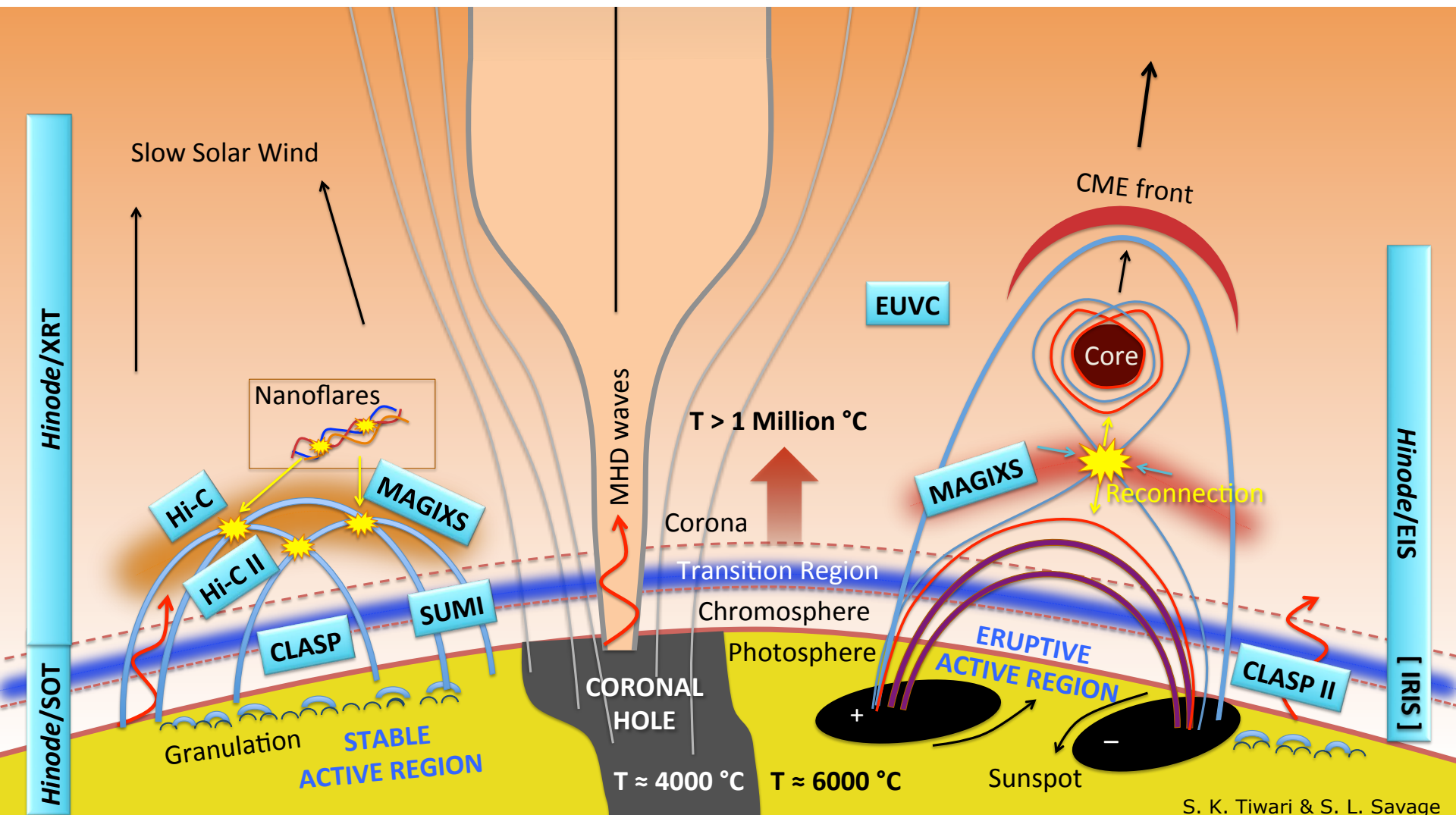
# Advancing Knowledge of the Coronal Heating Problem using the Sounding Rocket Platform



Dr. Amy Winebarger

NASA Marshall Space Flight Center

# Sounding Rocket Instruments at MSFC





# Major Science Goals

## BOX 10.1 SOLAR AND HELIOSPHERIC PHYSICS PANEL'S MAJOR SCIENCE GOALS AND ASSOCIATED ACTIONS

**SHP1. Determine how the Sun generates the quasi-cyclical variable magnetic field that extends throughout the heliosphere.**

- a. Measure and model the near-surface polar mass flows and magnetic fields that seed variations in the solar cycle.
- b. Measure and model the deep mass flows in the convection zone and tachocline that are believed to drive the solar dynamo.
- c. Determine the role of small-scale magnetic fields in driving global-scale irradiance variability and activity in the solar atmosphere.

**SHP2. Determine how the Sun's magnetism creates its dynamic atmosphere.**

- a. Determine whether chromospheric dynamics is the origin of heat and mass fluxes into the corona and solar wind.
- b. Determine how magnetic free energy is transmitted from the photosphere to the corona.
- c. Discover how the thermal structure of the closed-field corona is determined.
- d. Discover the origin of the solar wind's dynamics and structure.

# Sounding Rocket Instruments at MSFC

**Hi-C I** (J. Cirtain, PI)

Flew from WSMR on July 11, 2012

**Hi-C II** (J. Cirtain, PI)

Will be launched July, 2016

**CLASP I** (A. Winebarger, PI)

Launched from WSMR on September 3, 2015

**CLASP II** (J. Cirtain, PI)

Proposed to launch Spring, 2018

**MaGIXS** (A. Winebarger, PI)

Will be launched in 2018-19

FLOWN

FUNDED

PROPOSED

## Goal for this talk –

- Scientific motivation for all instruments
- Give first results from flights
- Describe sub-orbital camera development at MSFC

# Sounding Rocket Instruments at MSFC

✓ **Hi-C I** (J. Cirtain, PI)

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FLOWN

FUNDED

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# Why the chromosphere? Why now?

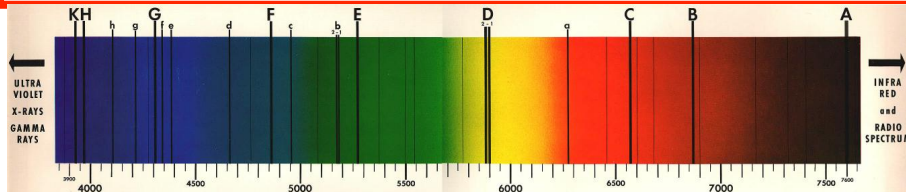
## **SHP2. Determine how the Sun's magnetism creates its dynamic atmosphere.**

- Determine whether chromospheric dynamics is the origin of heat and mass fluxes into the corona and solar wind.
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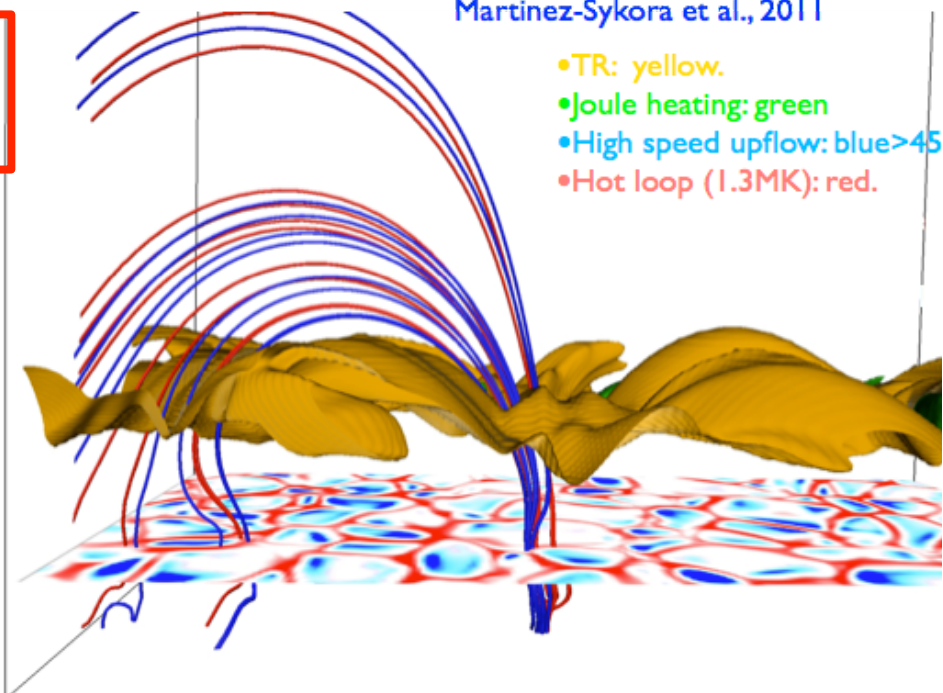
Solar and Space Physics: A Science for a Technological Society, 2013

Advances in theoretical modeling of the chromosphere and transition region allow for prediction and interpretation of the results.

Magnetically sensitive spectral lines formed in chromosphere are not in the visible wavelength range, so measurements have to go above atmosphere.



Martinez-Sykora et al., 2011



# Chromospheric Lyman-Alpha Spectropolarimeter (CLASP)

**Science Goal 1:** Detect scattering polarization in the wings of Lyman-alpha.

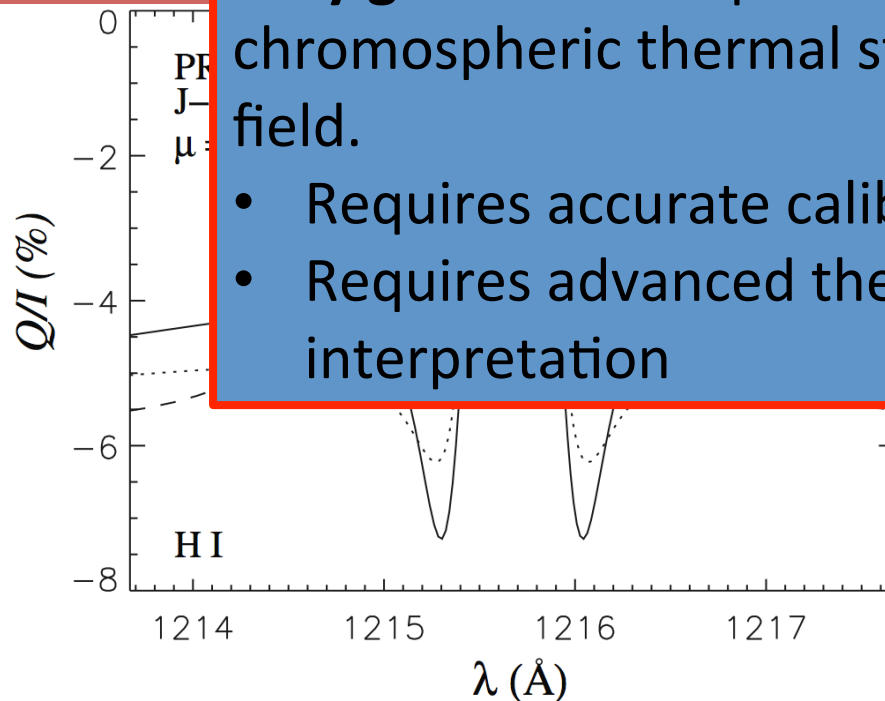
- Sensitive to the thermal structure of the chromosphere.
- Not sensitive to magnetic field
- Magnitude

**Science Goal 2:** Detect polarization in the line core.

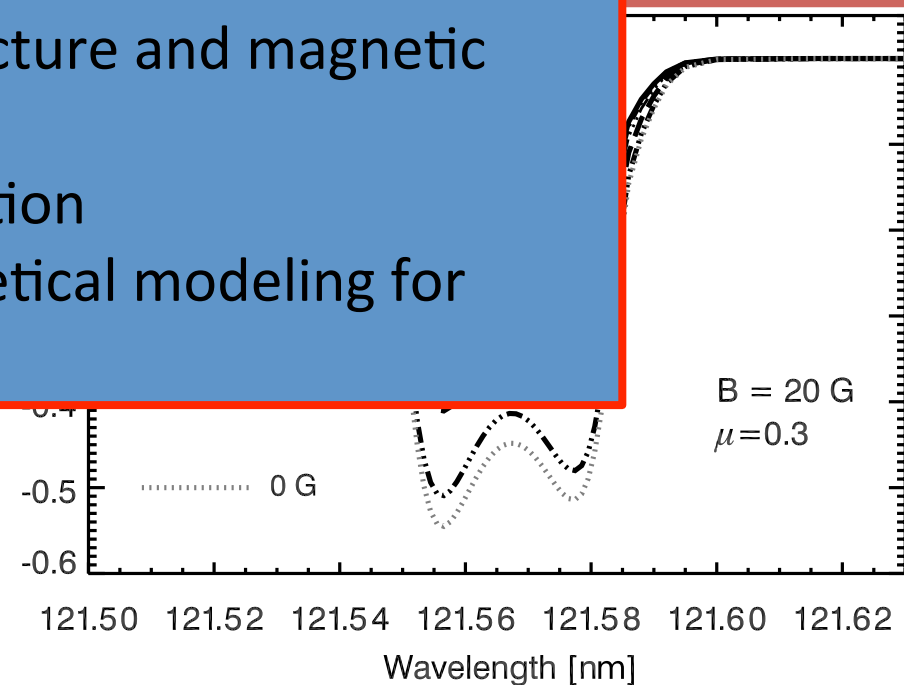
- Modified by the magnetic field through Hanle effect
- Magnitude of the polarization is  $\sim 0.1\%$
- Accuracy required technological advances in detector systems

**Holy grail:** Use the polarization to infer the chromospheric thermal structure and magnetic field.

- Requires accurate calibration
- Requires advanced theoretical modeling for interpretation

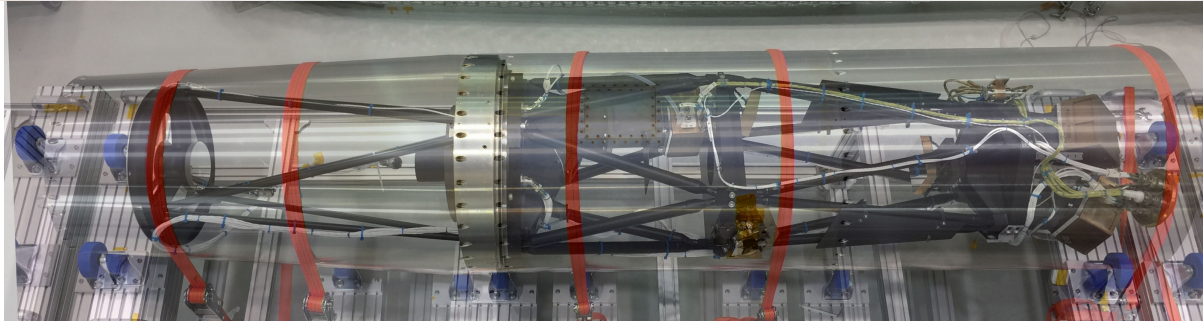


Belluzzi et al. 2012



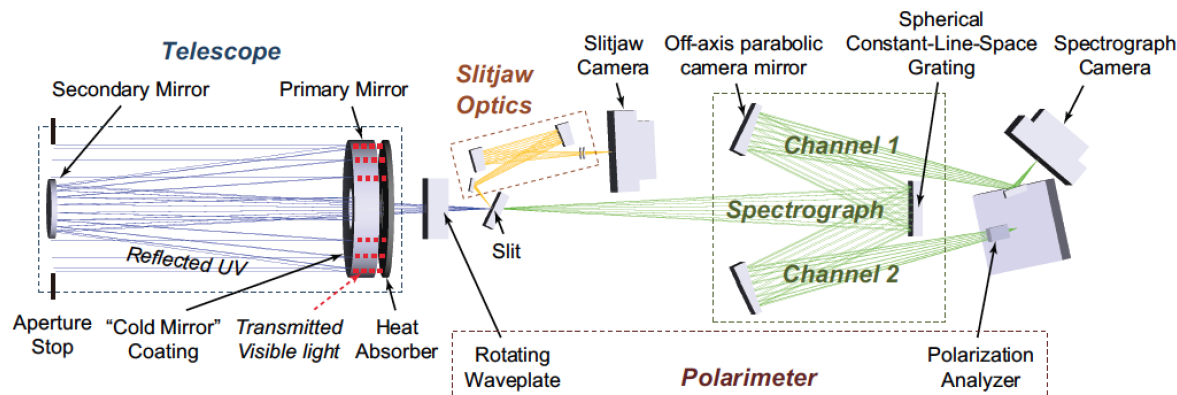
Trujillo Bueno et al. 2011

# Chromospheric Lyman-Alpha Spectropolarimeter (CLASP)



CLASP is a dual channel spectropolarimeter to measure the polarization of Lyman-alpha.

CLASP was designed and built through an international partnership. Scientists from 11 organizations and 6 countries form the CLASP team. Primary teams and responsibilities are listed below.



MSFC/USA (PI: A. Winebarger) – Cameras, avionics, project management, coordination w/ NASA launch team

NAOJ & JAXA/Japan (Co-PI: R. Kano) – Optics & opto-mechanics, instrument structure

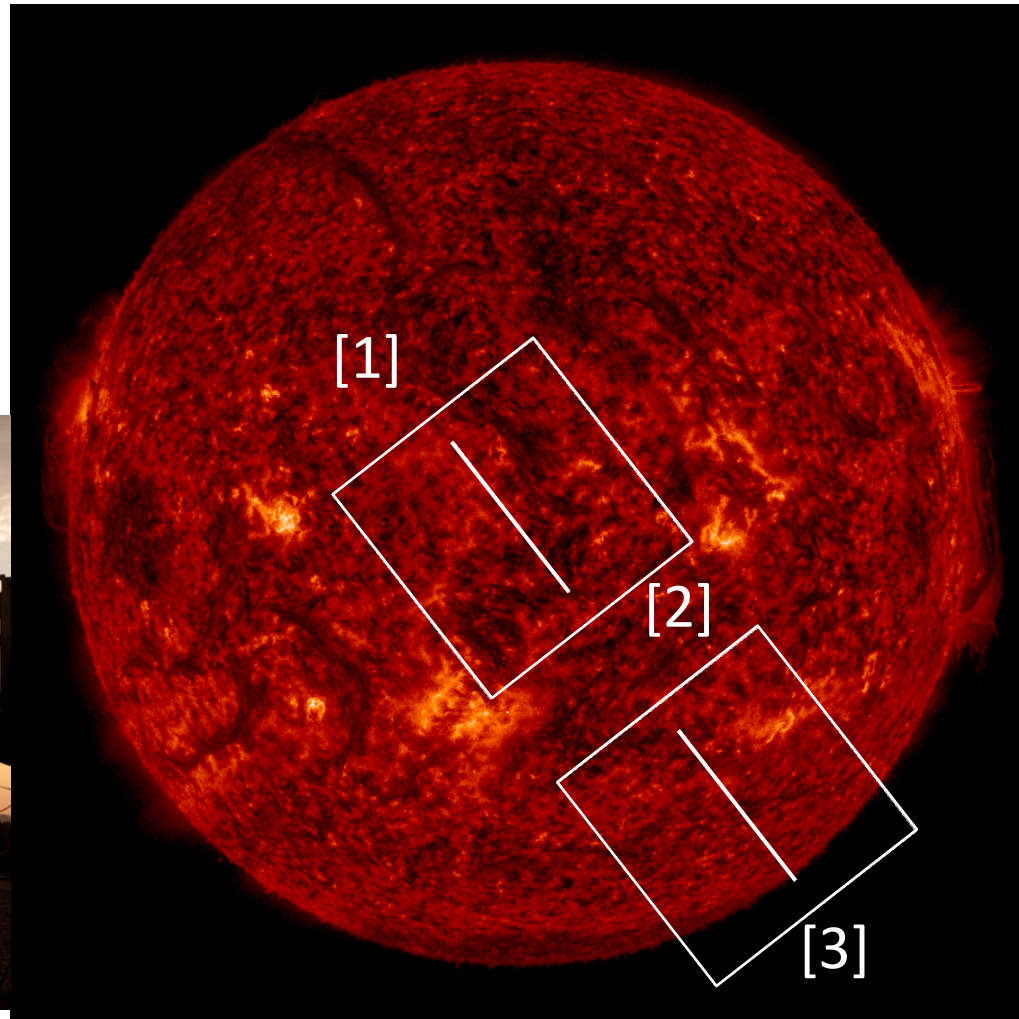
IAS/France (Co-PI: F. Auchère) – Diffraction Grating

IAC/Spain (Co-PI: J. Trujillo Bueno) – Theoretical predictions and modeling of the Hanle effect



# Chromospheric Lyman-Alpha Spectropolarimeter (CLASP)

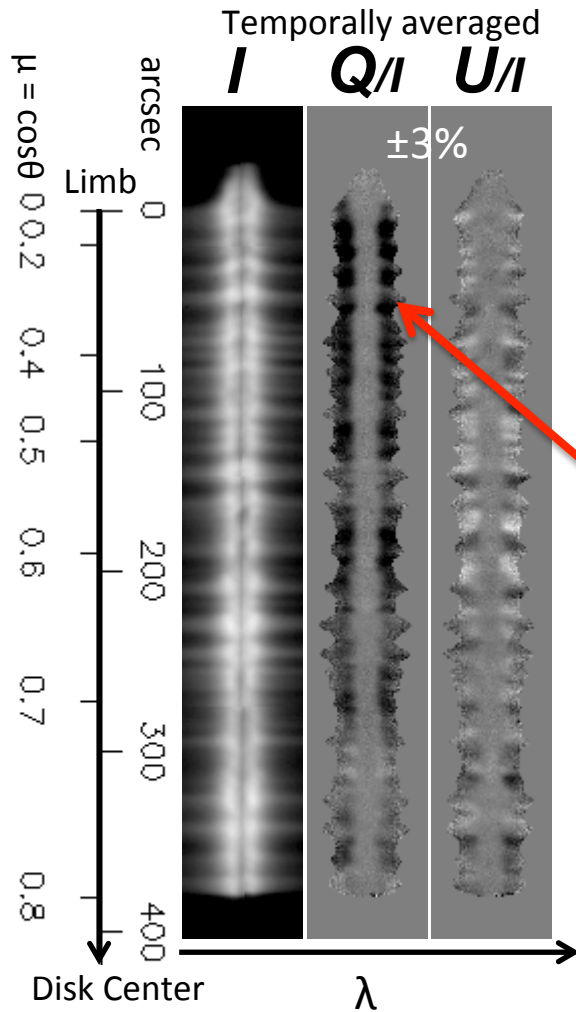
CLASP was launched on September 3, 2015 from White Sand Missile Range



# Chromospheric Lyman-Alpha Spectropolarimeter (CLASP)

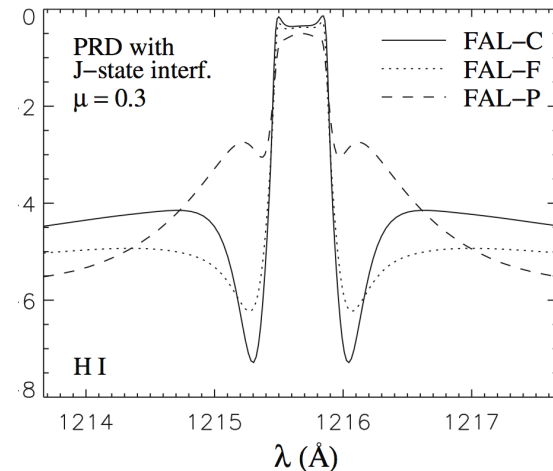
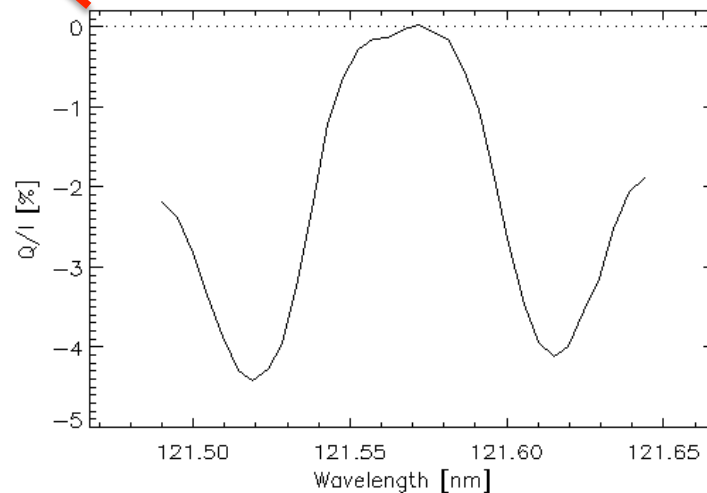


# CLASP Initial Results

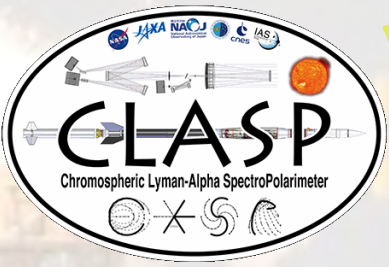


Further calibrations/investigations are required, but ...

- **A few %** of polarization in the wing, and **a few of 0.1 %** in the core.
- A clear **C-to-L variation** in the wing of Q/I.
- Small-scale structures along the slit.
- Q/I profile is essentially **consistent with the model prediction**.





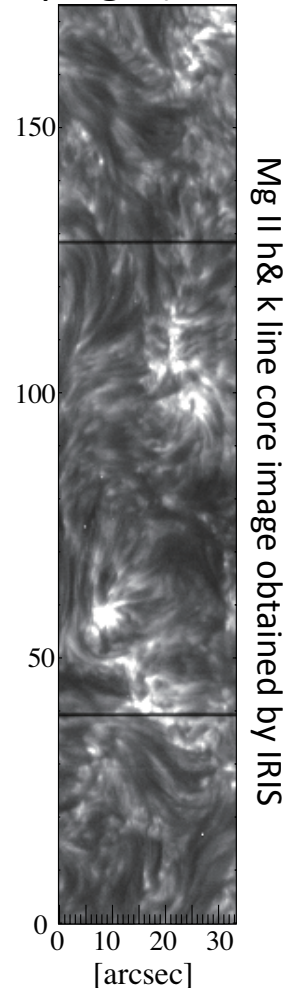
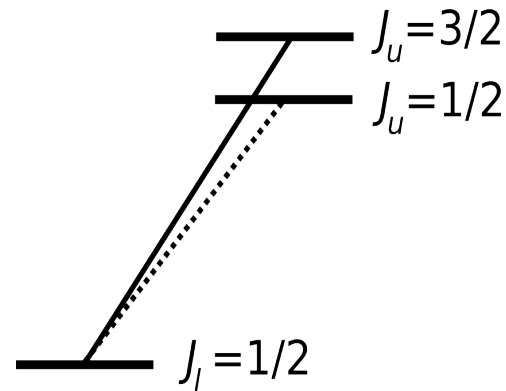
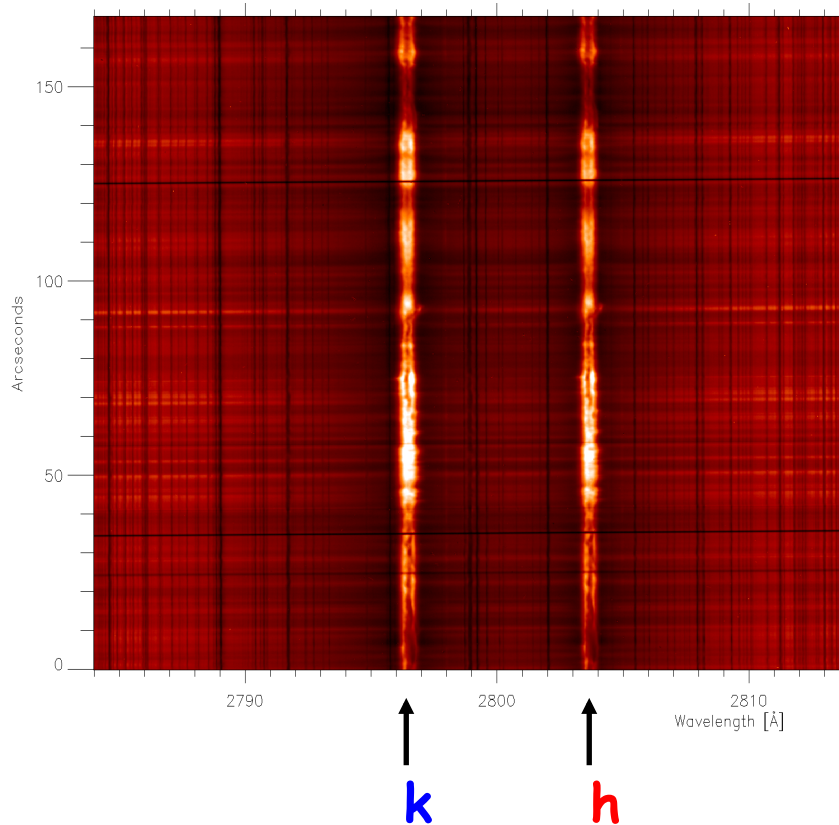


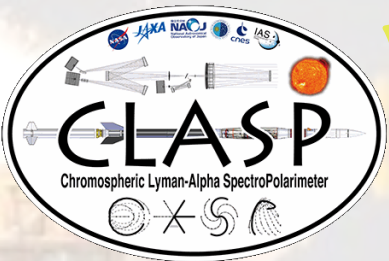
2

# What is next for CLASP?

CLASP 2 proposes to change the wavelength to Mg II h&k, another set of magnetically sensitive spectral lines in the UV at  $\sim 280$  nm.

Observing target: QS and plage (if available)

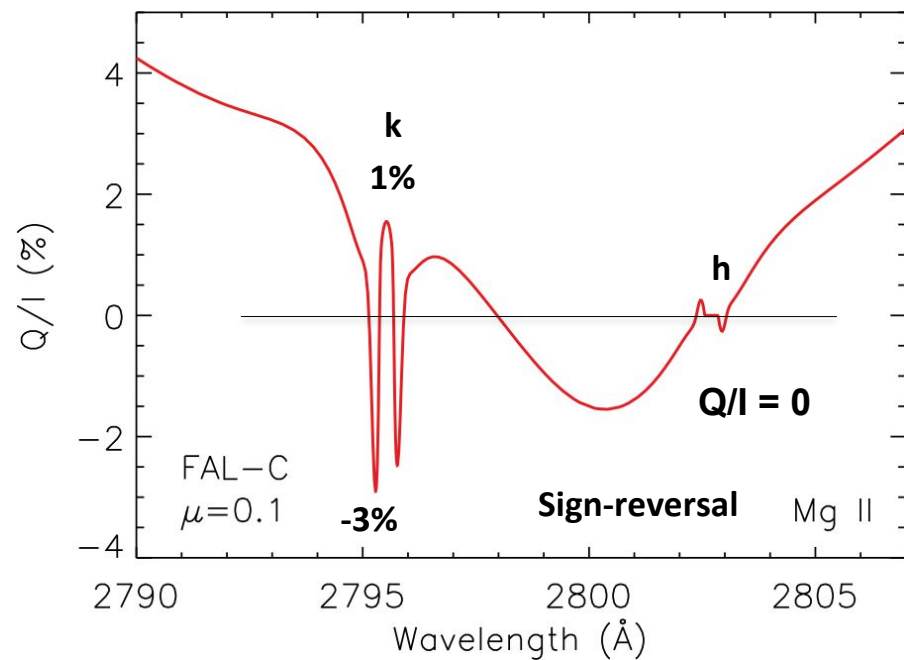




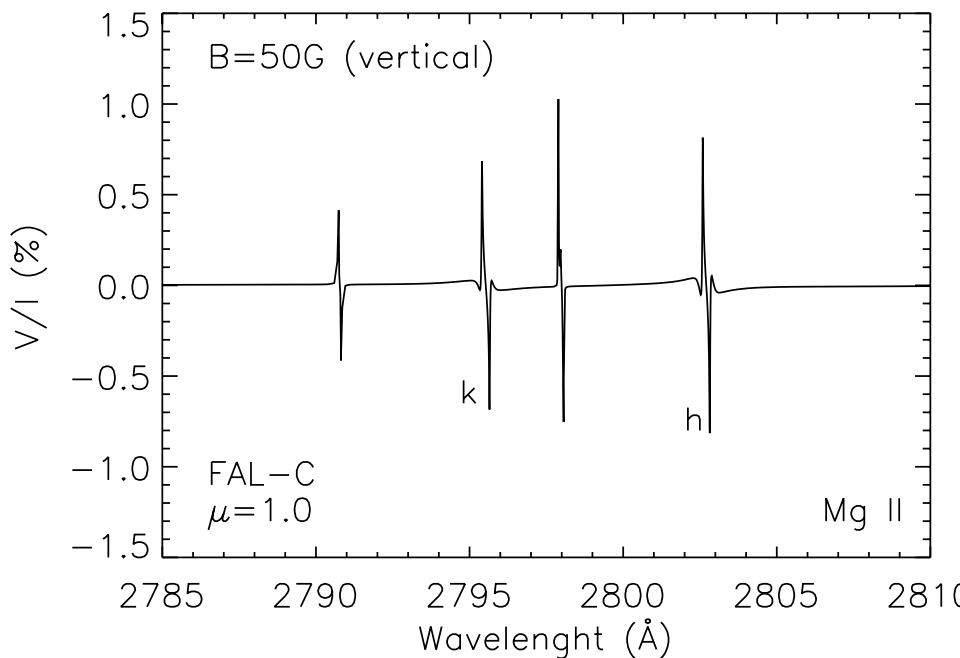
2

# What is next for CLASP?

Linear polarization sensitive to scattering polarization and Hanle effect from 5-50 G.



Circular polarization sensitive to Zeeman effect for  $B > 50$  G.



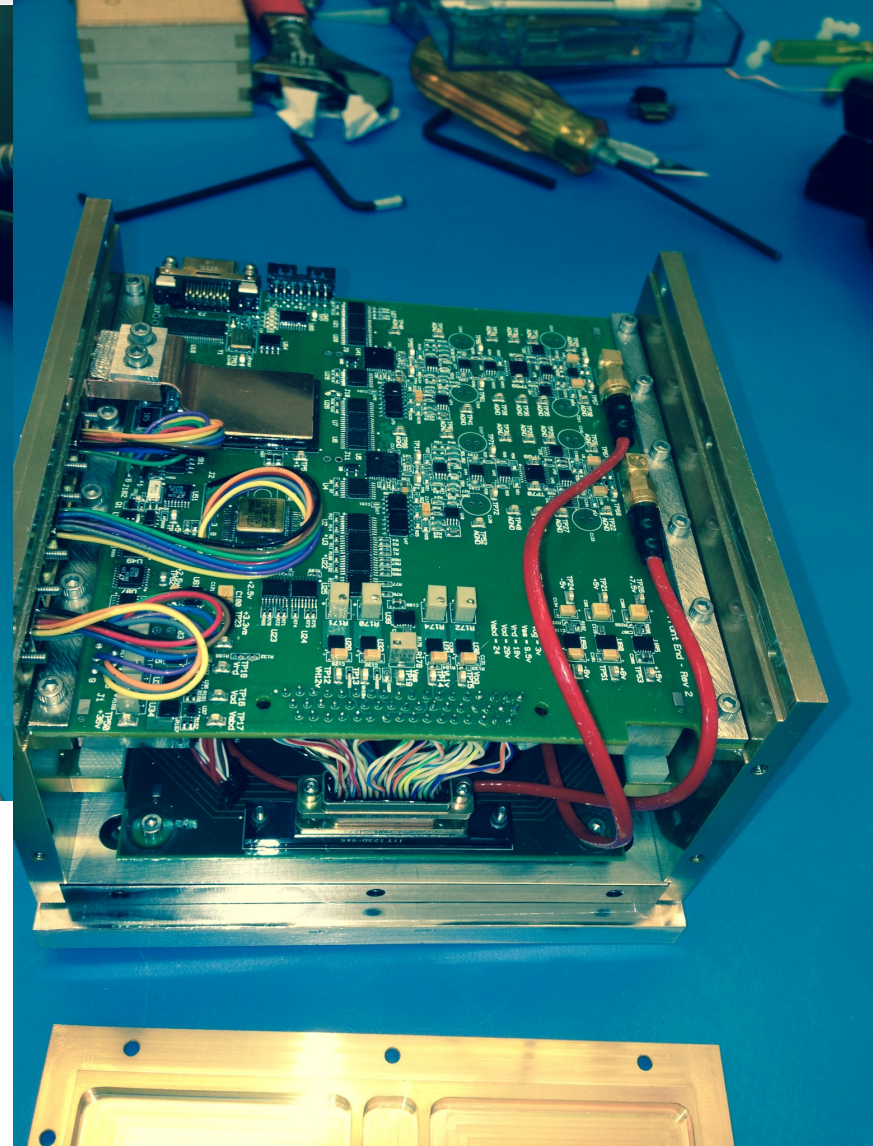
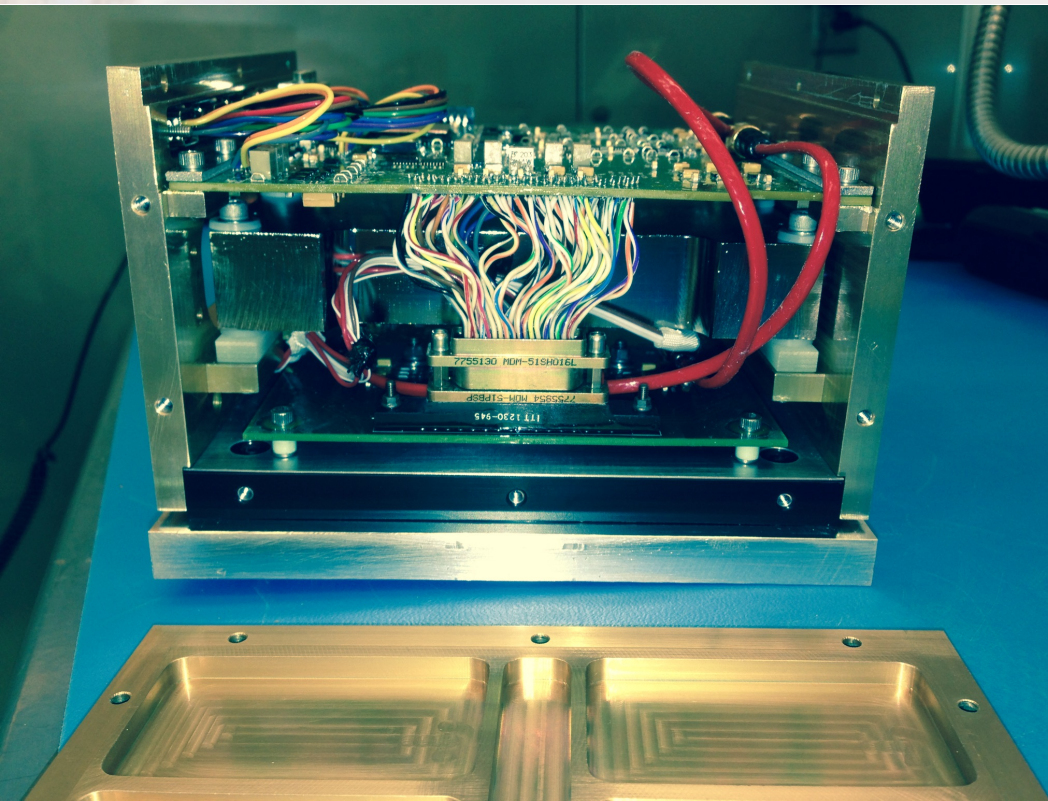
Proposed to fly in Spring 2018.

# Low Noise Camera Development

- To achieve the 0.03% polarization accuracy required by CLASP, we required detectors with less than  $25e^-$  total noise.
- We developed a 512x512 frame transfer camera at MSFC suitable for sub orbital instruments.
- 3 flight cameras were built (2 SP, 1 SJ)
- Each contain a back-thinned e2v CCD57-10 detector, coated with lumogen.
- Noise calculations from flight data demonstrate  $<6e^-$  noise RMS noise in all cameras.

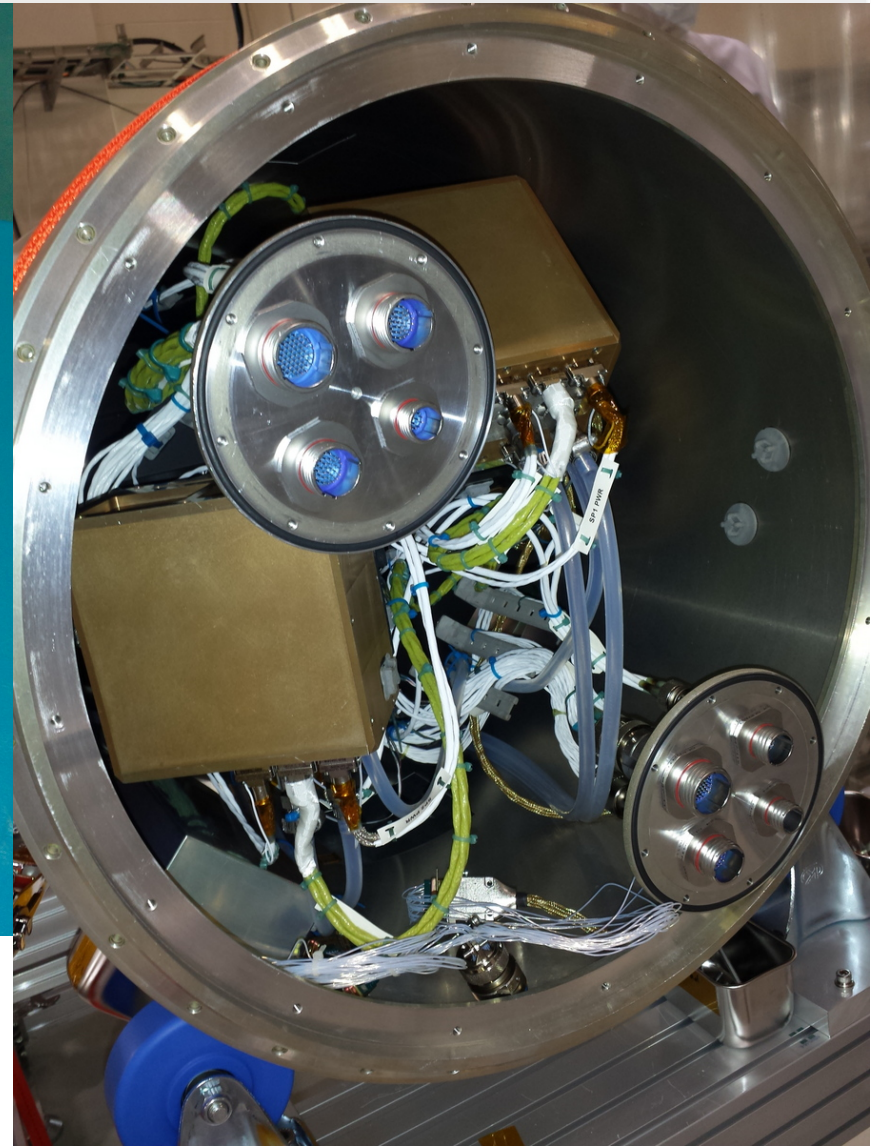
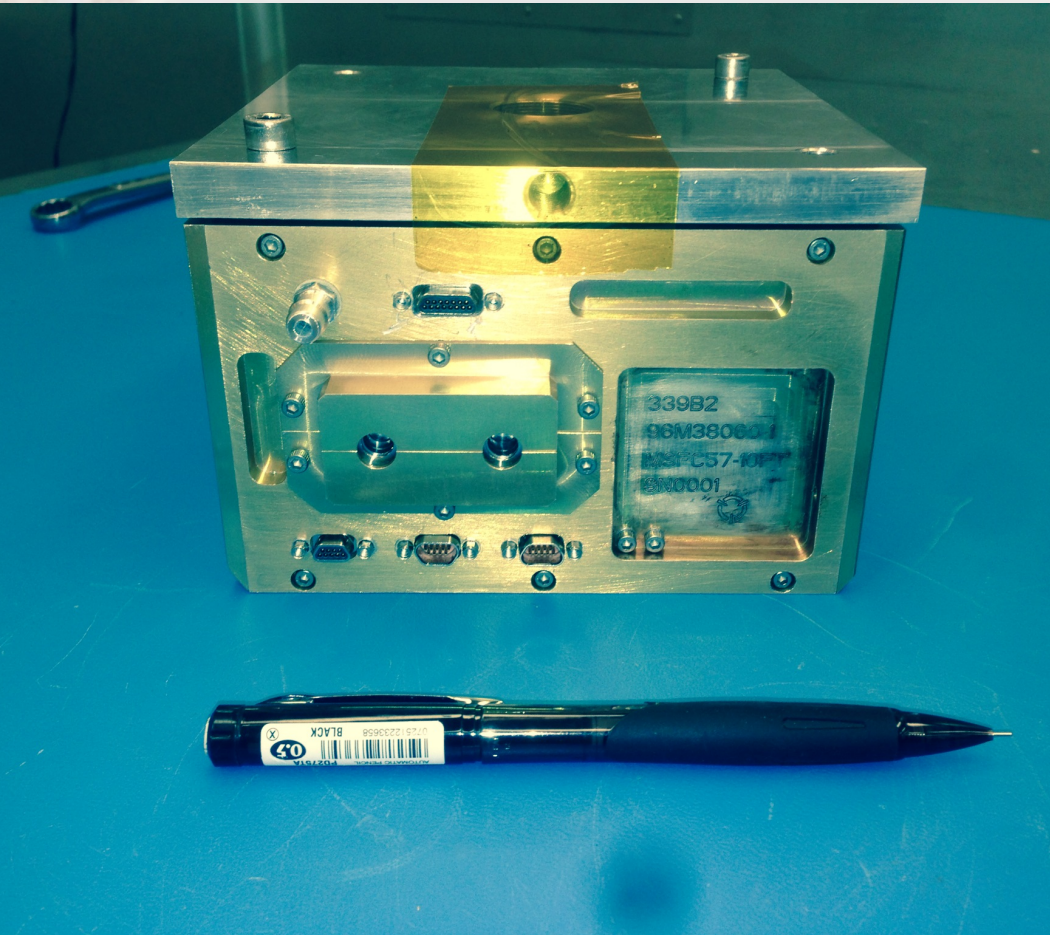


# Low Noise Camera Development





# Low Noise Camera Development



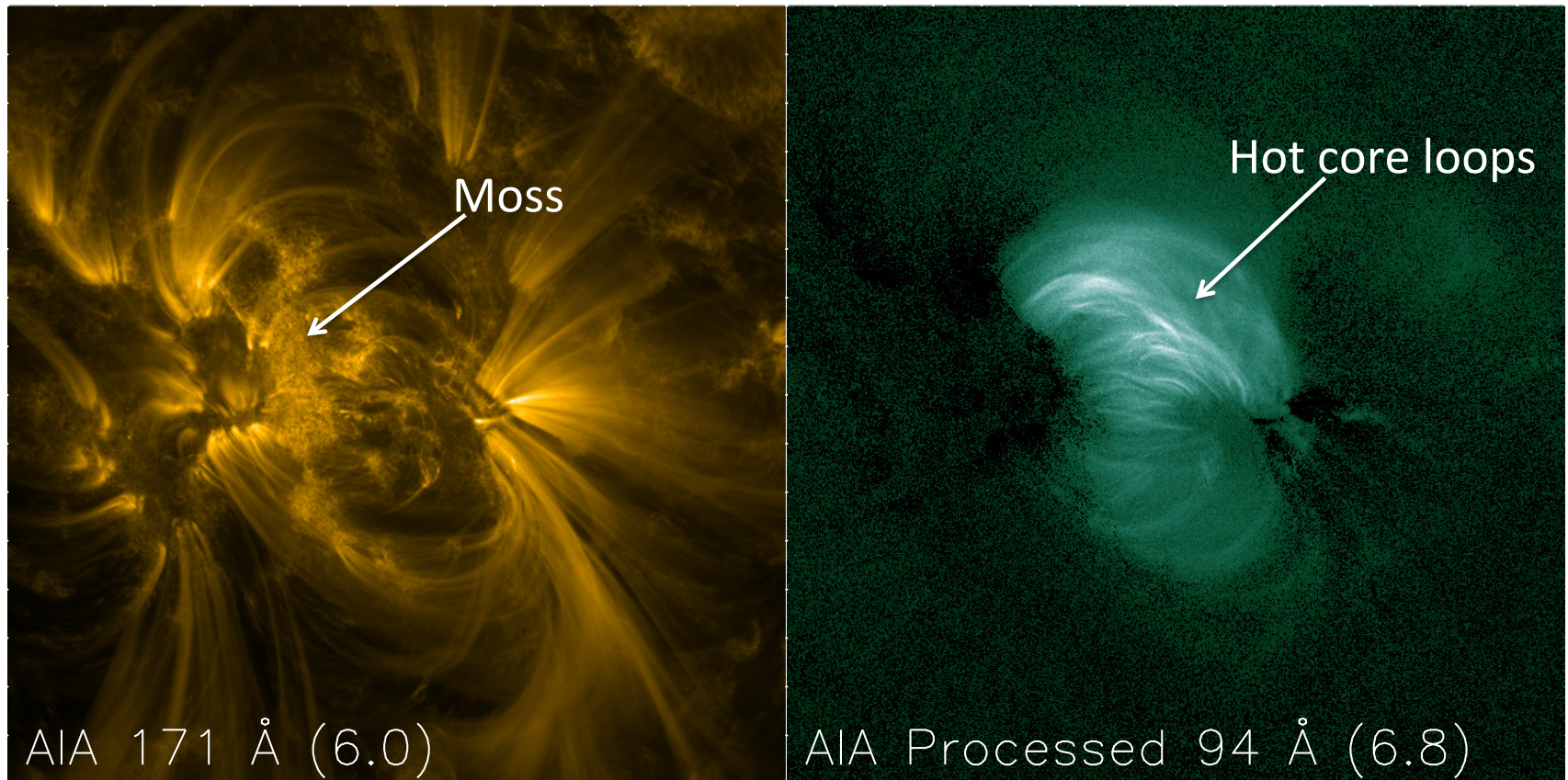
# Low Noise Camera Development

- The design is currently being expanded for a 2kx2k CCD.
- Hi-C, MaGIXS, and ESIS (MSU sounding rocket) will make use of the new design.



# Marshall Grazing Incident X-ray Spectrometer (MaGIXS)

The science goal of MaGIXS is to determine the frequency of heating in active region cores.



Is heating sporadic (nanoflares) or frequent (waves)?

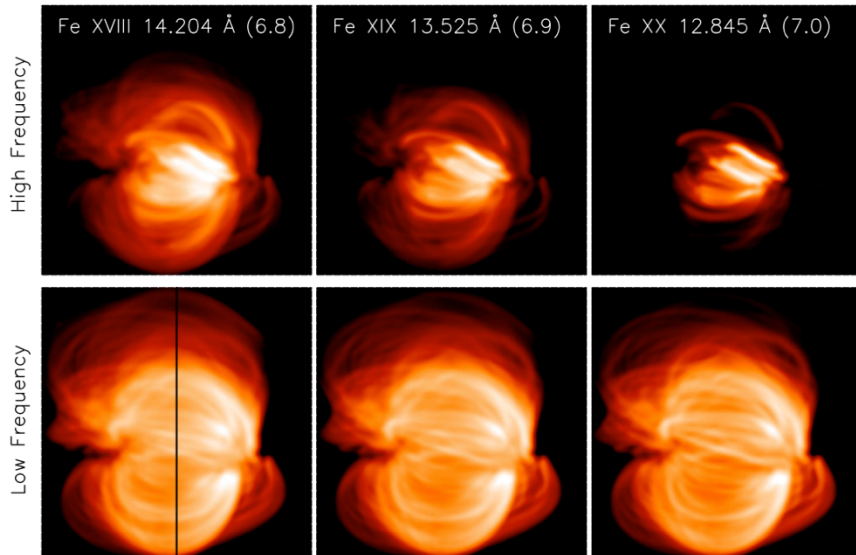


# Marshall Grazing Incident X-ray Spectrometer (MaGIXS)

MaGIXS will make four key observations to differentiate between sporadic and frequent heating.

- Relative amount of high temperature plasma
- Elemental abundances
- Temporal variability of high temperature plasma
- Likelihood of non-Maxwellian distributions

# Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



Simulated active region core  
using 0-D EBTEL:

- Random heating events
- Heating event cadence 1575 s  
versus 6300 s

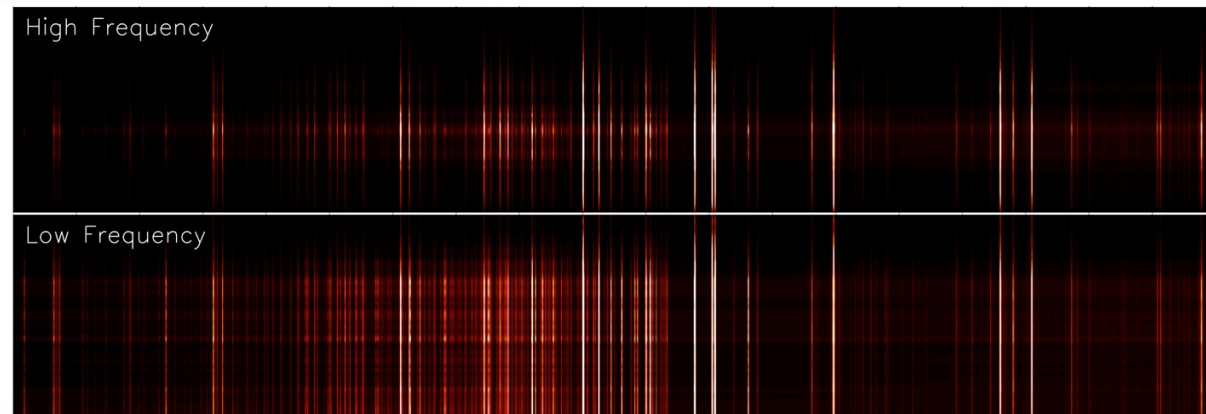
**Expected emission quite different at higher  
temperature lines.**

## Simulated MaGIXS spectra

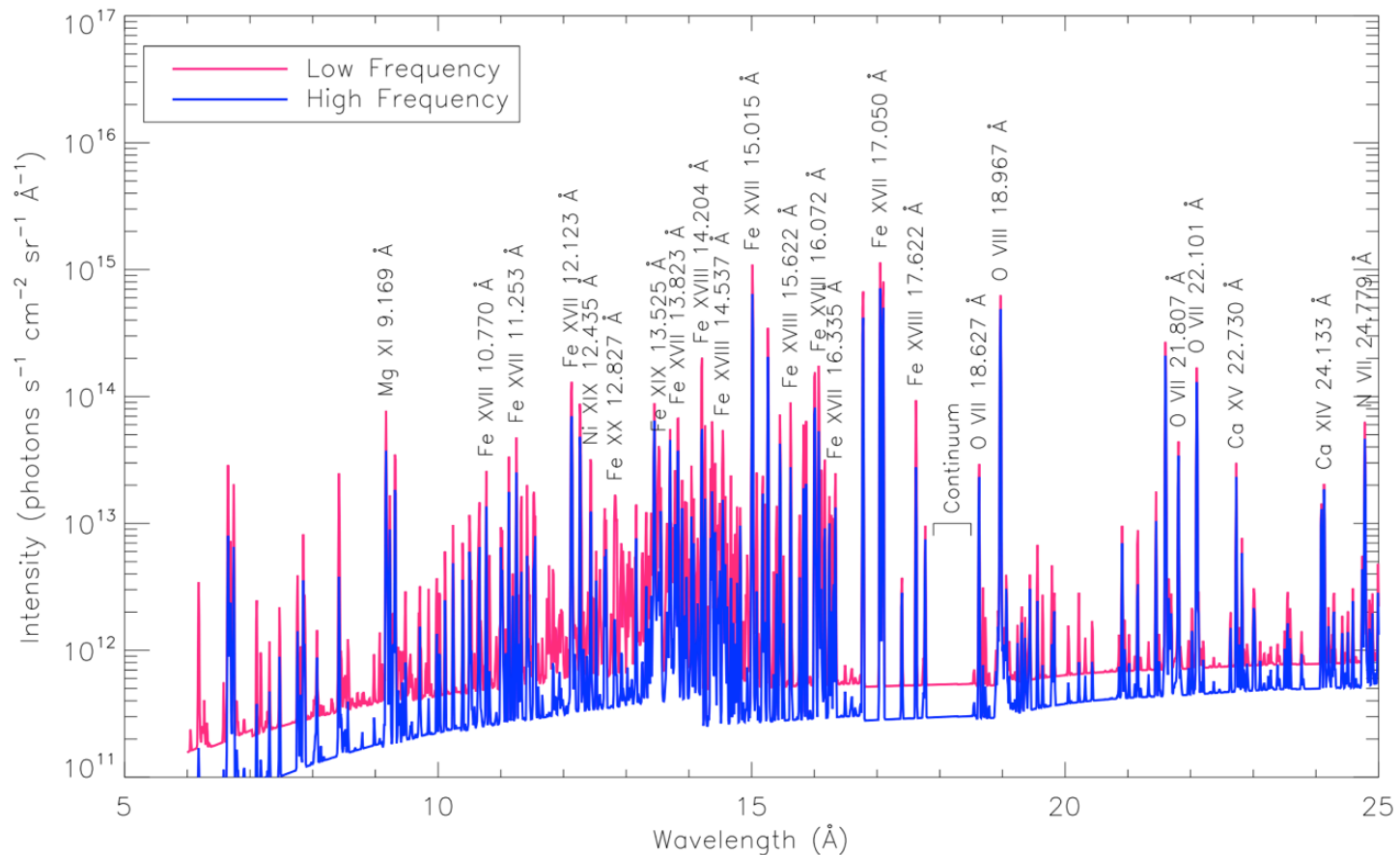
Biggest difference in Fe XX  
(12.845 Å).

Multiple high temperature  
spectra lines necessary for  
interpretation.

Fe XX 12.845 Å    Fe XIX 13.525 Å    Fe XVIII 14.204 Å    Fe XVII 15.015 Å    O VIII 18.696 Å    O VII 21.601 Å



# Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



**Simulated spectra from a single spatial position along the MaGIXS slit.**

# Marshall Grazing Incident X-ray Spectrometer (MaGIXS)

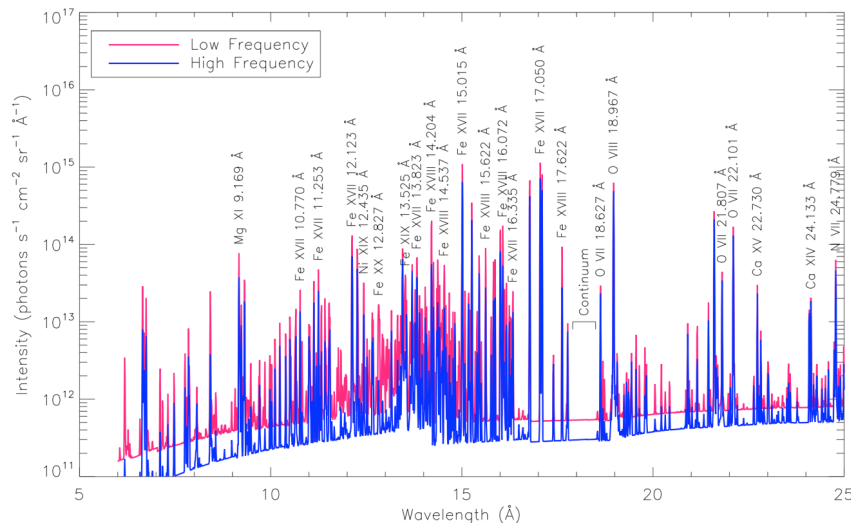
Trends in variability indicate that the FIP bias is proportional to the plasma's time of confinement.

**Abundance measurements may be an indicator of the frequency of heating.**

- Photospheric: *sporadic*
- Coronal: *high frequency*

Spectral Line	Log Temperature
Mg XII 8.42 Å	6.9
Mg XI 9.16 Å	6.4
Ne X 12.13 Å	6.6
Ne IX 13.45 Å	6.2
Fe XVIII 14.21 Å	6.8
Fe XVII 15.01 Å	6.6
O VIII 18.97 Å	6.4
O VII 21.60 Å	6.3

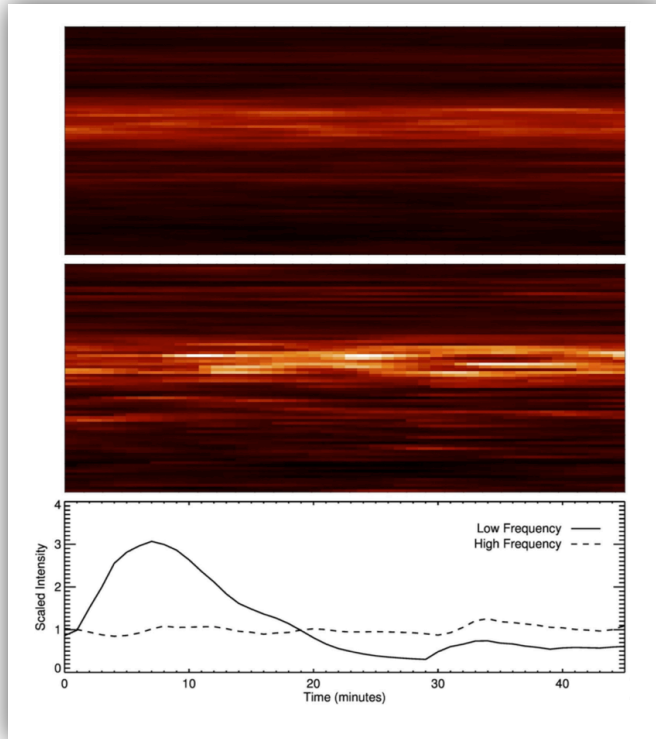
*Relative abundances largely independent of plasma temperature.*



The **spatially and spectrally resolved MaGIXS solar spectrum** will provide relative and absolute abundances for determining the FIP bias in several AR structures.



# Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



A statistical analysis of AR light curves can also be used to understand heating frequency:

Individual impulsive heating event (low frequency) = steep rise --> slower decay

**Impulsive heating results in a skewed distribution, definitely measurable by MaGIXS.** Use Fe XVII lightcurves to determine if *Hinode*/XRT skewness due to high temperature fluctuations versus cool contributions or noise.

If high-T variability confirmed, **timescales can be used to determine the heating frequency.**

**Non-Maxwellian distributions would strongly indicate impulsive, infrequent coronal heating** from magnetic reconnection or wave-particle interactions. MaGIXS spectral range optimal for this search due to high-energy excitation thresholds (e.g., ratio between Fe XVIII lines and *SDO*/AIA 94 Å bandpass).

# Marshall Grazing Incident X-ray Spectrometer (MaGIXS)

## Science Objectives

1) The relative amount of high-temperature plasma in different solar structures.

2) The elemental abundances in different solar structures.

3) The temporal variability at high temperatures in different solar structures.

4) The likelihood of Maxwellian or non-Maxwellian distributions.

## Science Requirements

Observe Fe XVII 15.01 Å (1,2,3), Fe XVIII 14.21 Å (1,2,4), Fe XIX 13.53 Å (1), Fe XX 12.85 Å (1), Mg XII 8.42 Å (1,2), Mg XI 9.16 Å (1,2), Ne X 12.13 Å (1,2), Ne IX 13.45 Å (1,2), O VIII 18.97 Å (1,2), O VII 21.60 Å (1,2)

Spectrally resolve strong spectral lines.

Differentiate structures along the slit

Temporal resolution of full spectra less than the lifetime of structures

Determine the overall morphology of active region (loop length and evolution)

Supporting observations in *Hinode*/XRT (3) and *SDO*/AIA 94 Å (4)

Temporal resolution of Fe XVII 15.01 Å of < 5s (3)

## Instrument Requirements

Observe 6-24 Å

Spectral resolution < 0.1 Å

Spatial resolution < 6"  
Slit length ~ 400"

Throughput to observe spectral lines during rocket flight.

Target: Medium-sized active region or larger

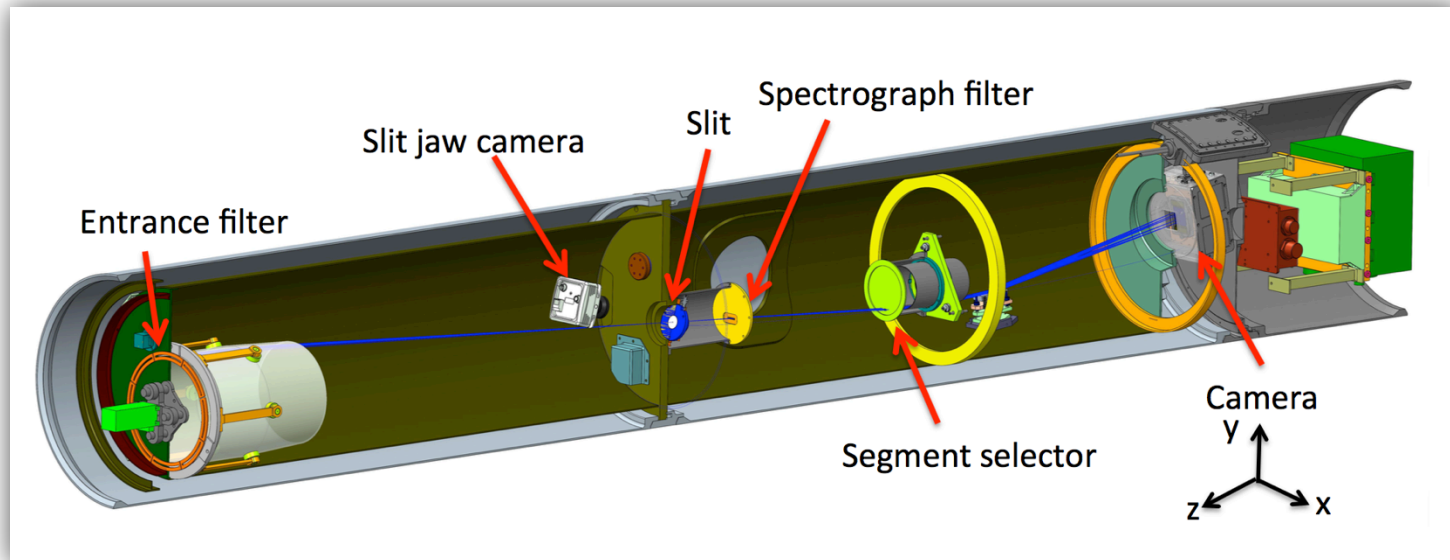
Slit jaw images to allow for co-alignment with other observatories

Supporting observation in space and ground based observatories

Camera read out < 5s.



# Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



Telescope: Wolter Type-I  
Effective Focal Length  $\sim 1$  m

Slit jaw imaging system for pointing and co-alignment

Detector : Low noise, 2kx1k frame transfer

Spectrograph: Two matched parabolic mirrors + Grating

6.0 - 24.0 Å (0.5 - 2.0 keV)

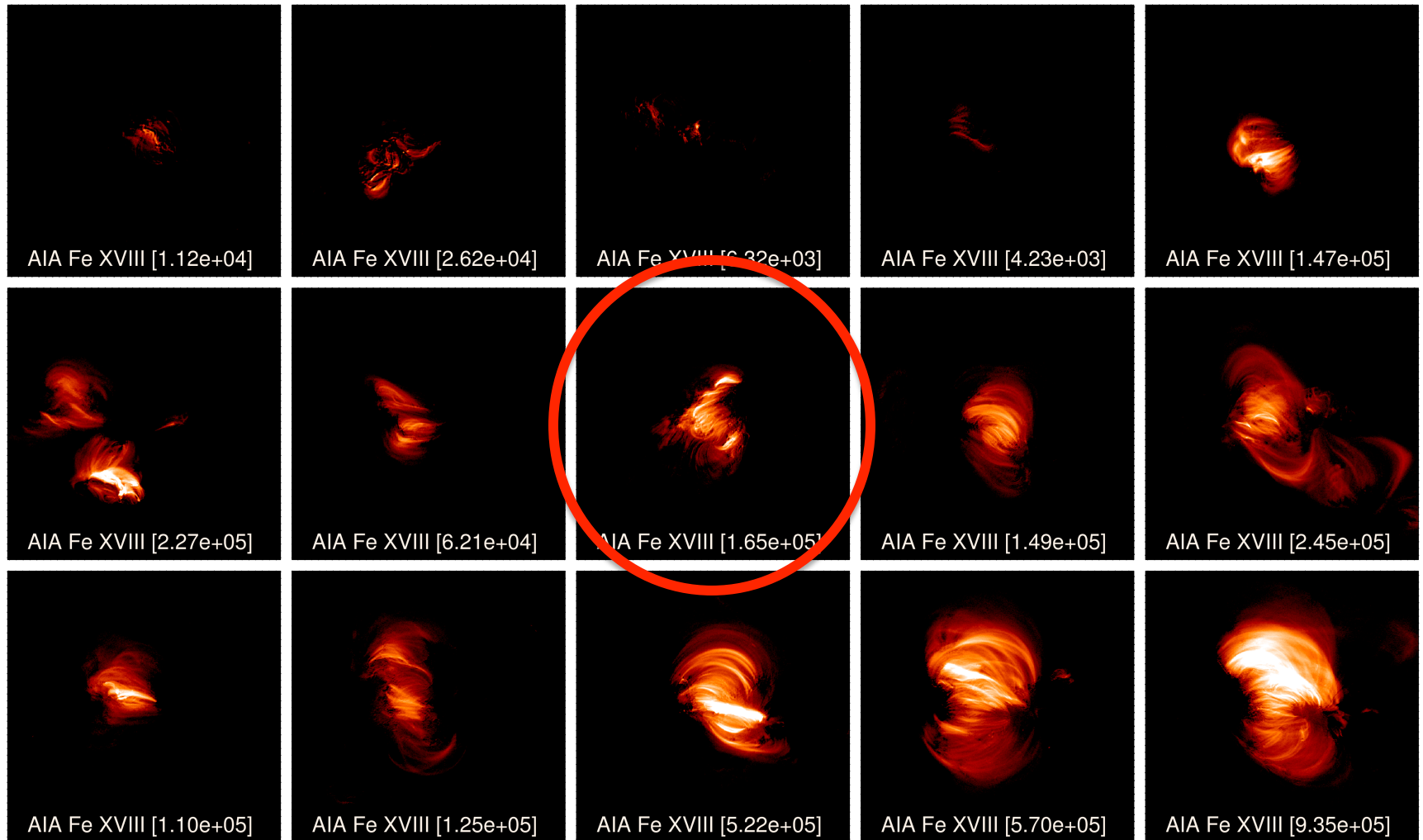
11 mÅ / pixel

2.8 arcsec / pixel

Grating: Blazed Planar Varied Line Space

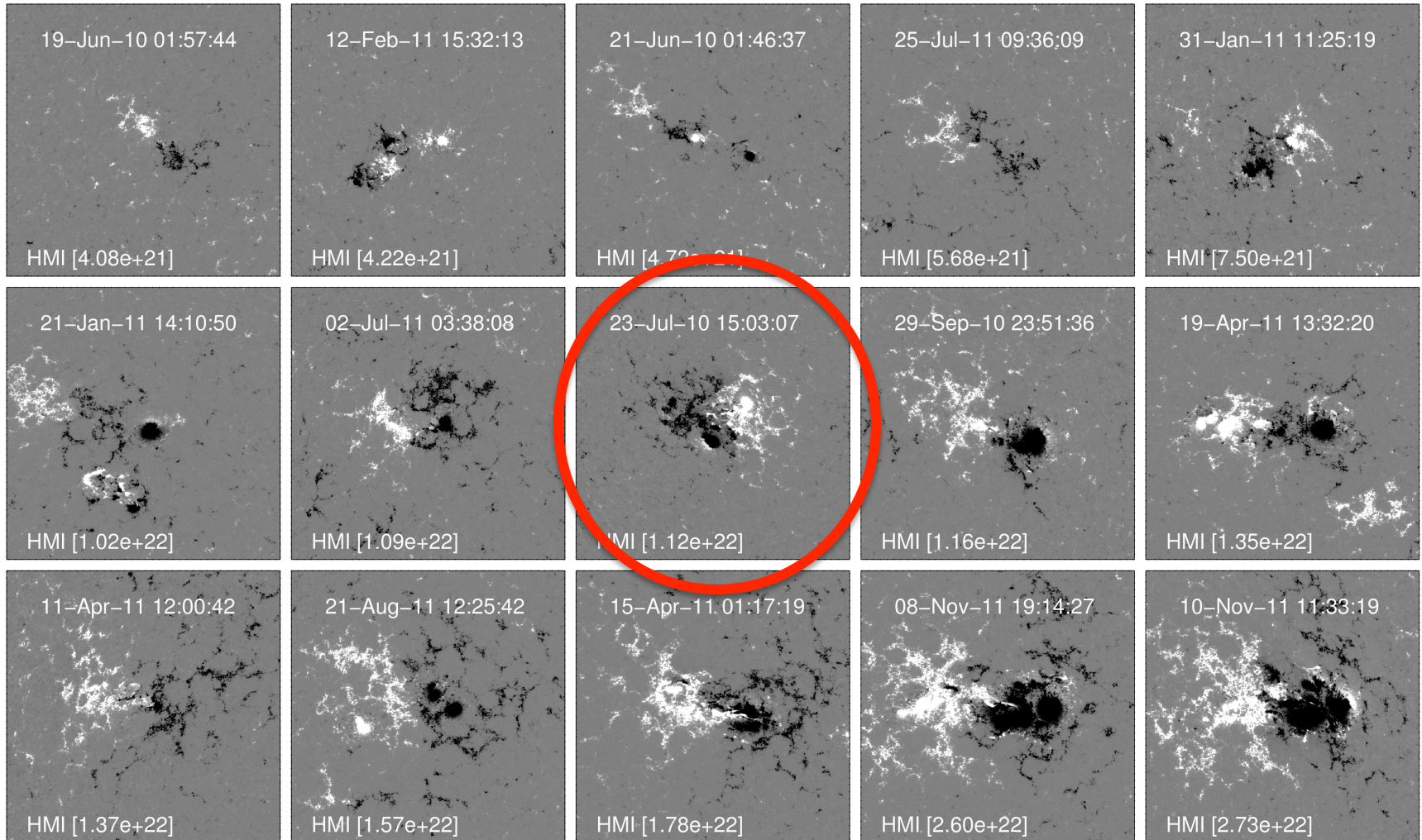
MaGIXS will be launched in summer 2018 or 2019.

# Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



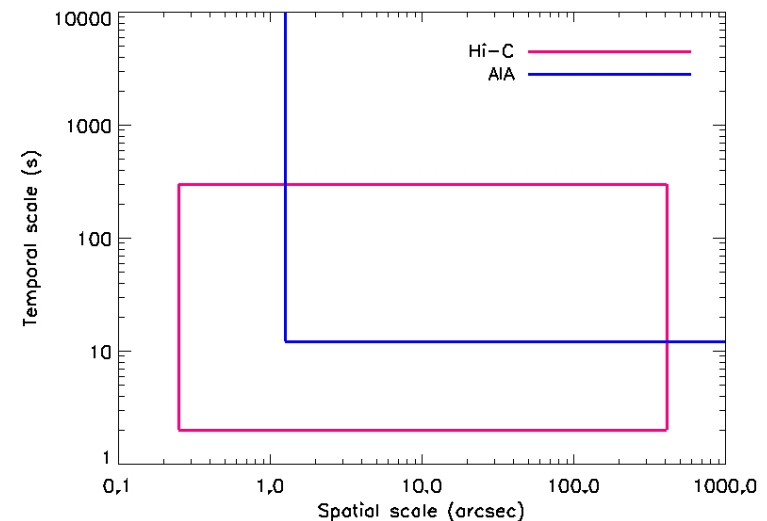
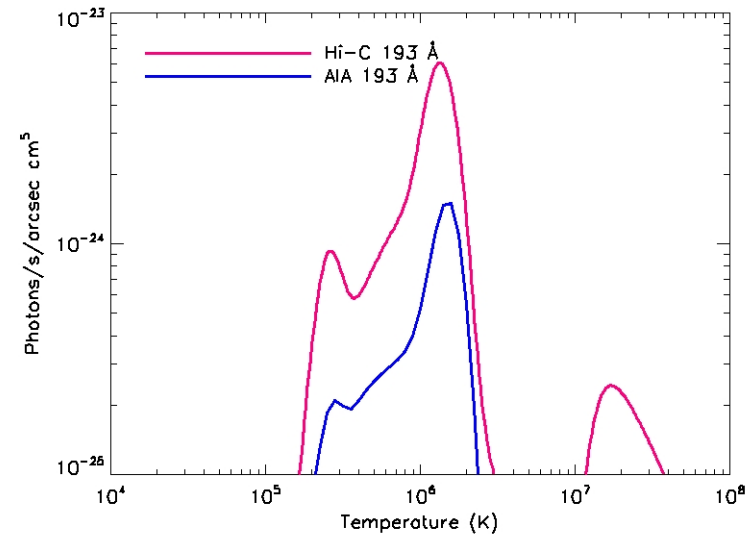


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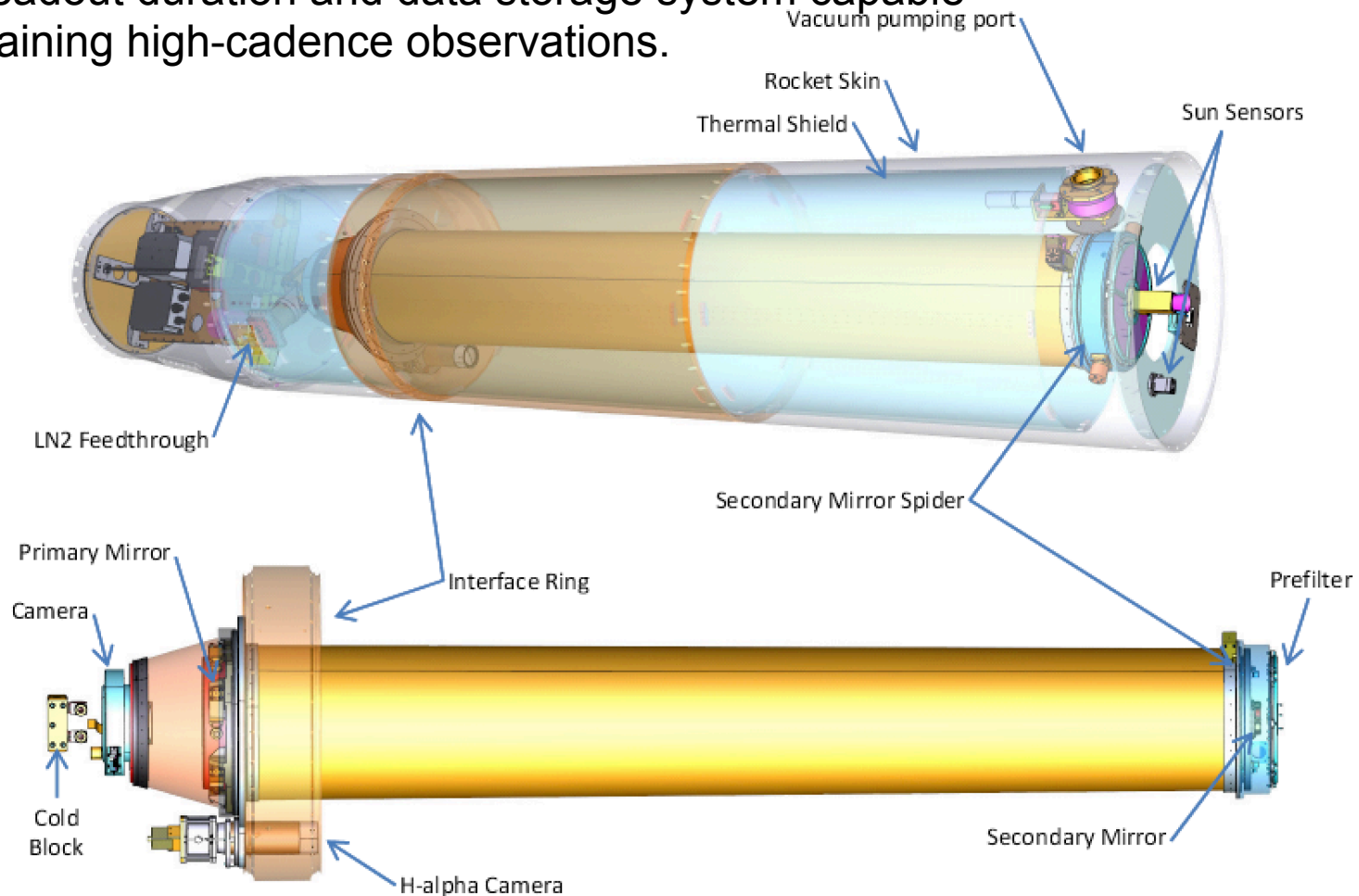
# High-resolution Coronal Imager (Hi-C)

- The Hi-C 193 Å passband is similar to the 193 Å passband on the Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA).
- Hi-C has roughly 5 times the effective area of AIA.
- The cadence of Hi-C is 2.5 – 6 times better than AIA.
- Hi-C collected data for 345 s.
- Small shift in pointing during flight
- Full frame (4kx4k) data
  - 30 full resolution images
  - 2 s exposures / 5 s cadence
- Partial frame (1kx1k) data
  - 86 full resolution image
  - 0.5 s exposures / 1.4 s cadence



# High-resolution Coronal Imager (Hi-C)

Telescope design capable of  $\sim 150\text{km}$  spatial resolution  
Pointing stability necessary to achieve resolution goal  
Image readout duration and data storage system capable  
of maintaining high-cadence observations.



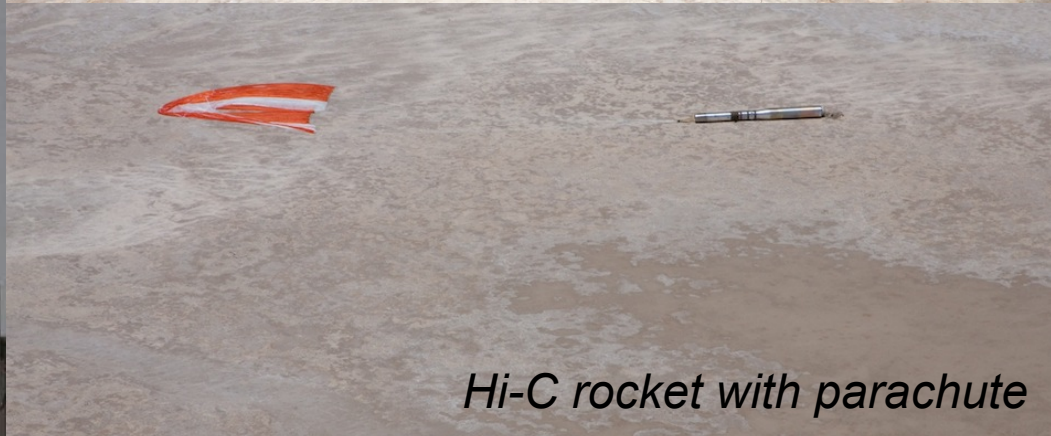


# High-resolution Coronal Imager (Hi-C)

*Hi-C Launch  
July 11, 2012*



*Hi-C recovery team*

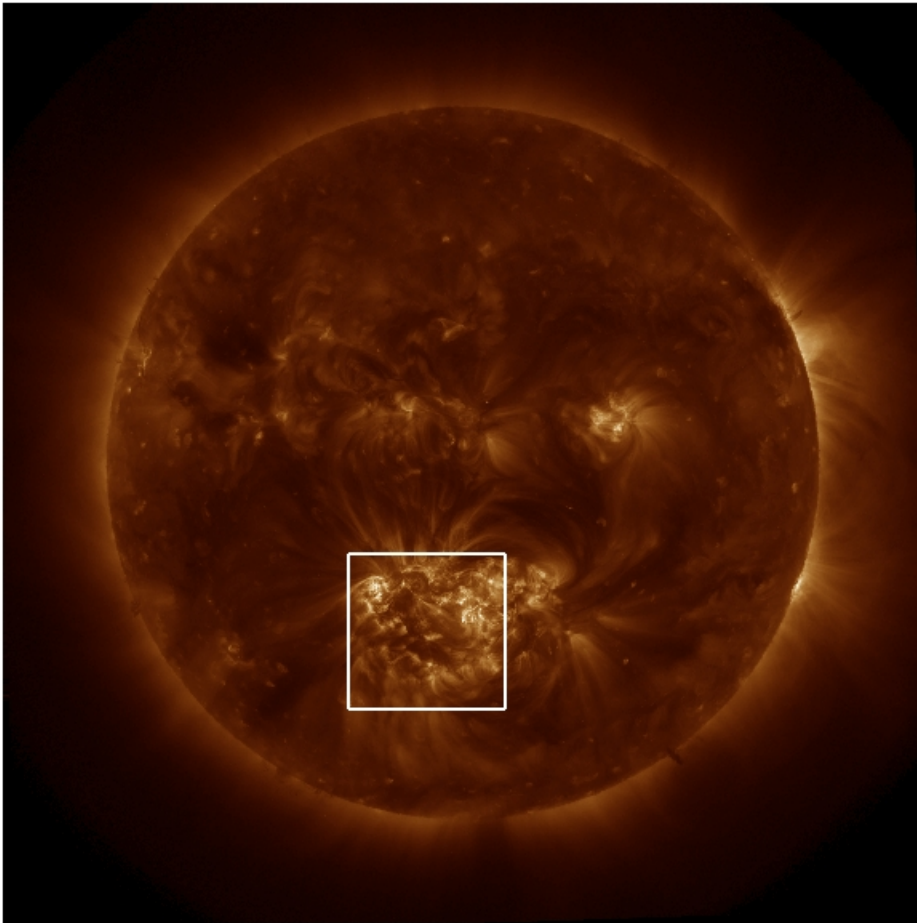


*Hi-C rocket with parachute*

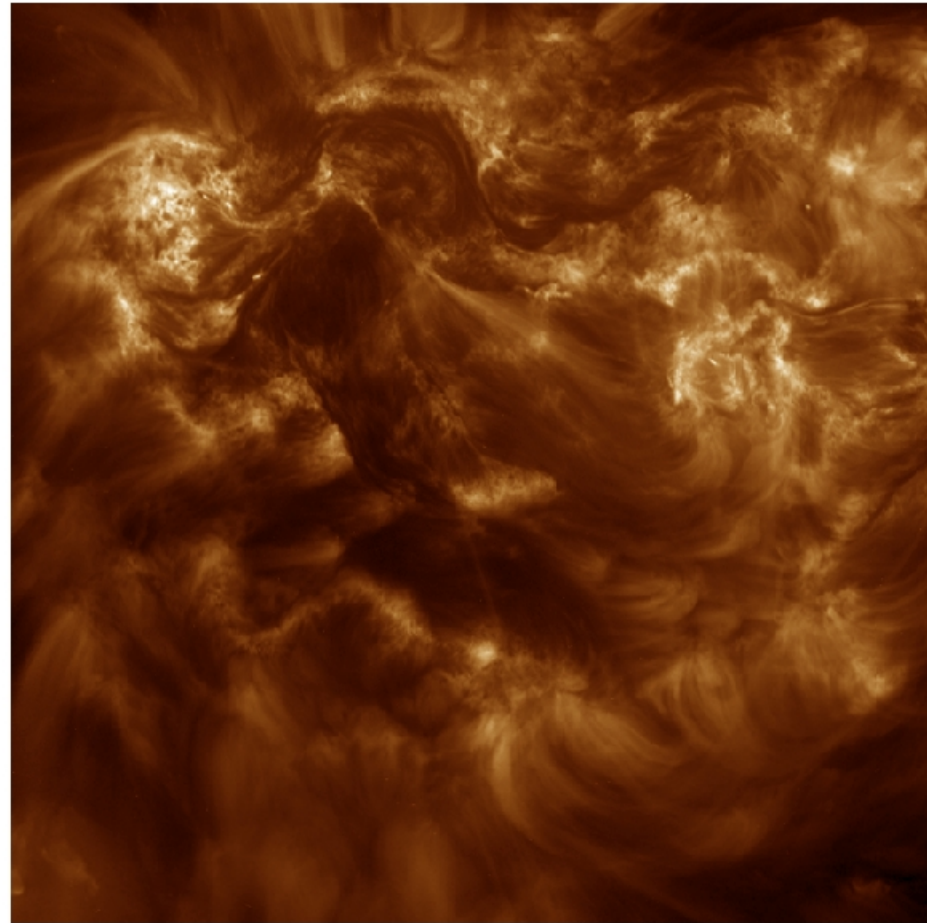


# High-resolution Coronal Imager (Hi-C)

AIA 193-Å 11-Jul-2012 18:55:07



Hi-C Field of View

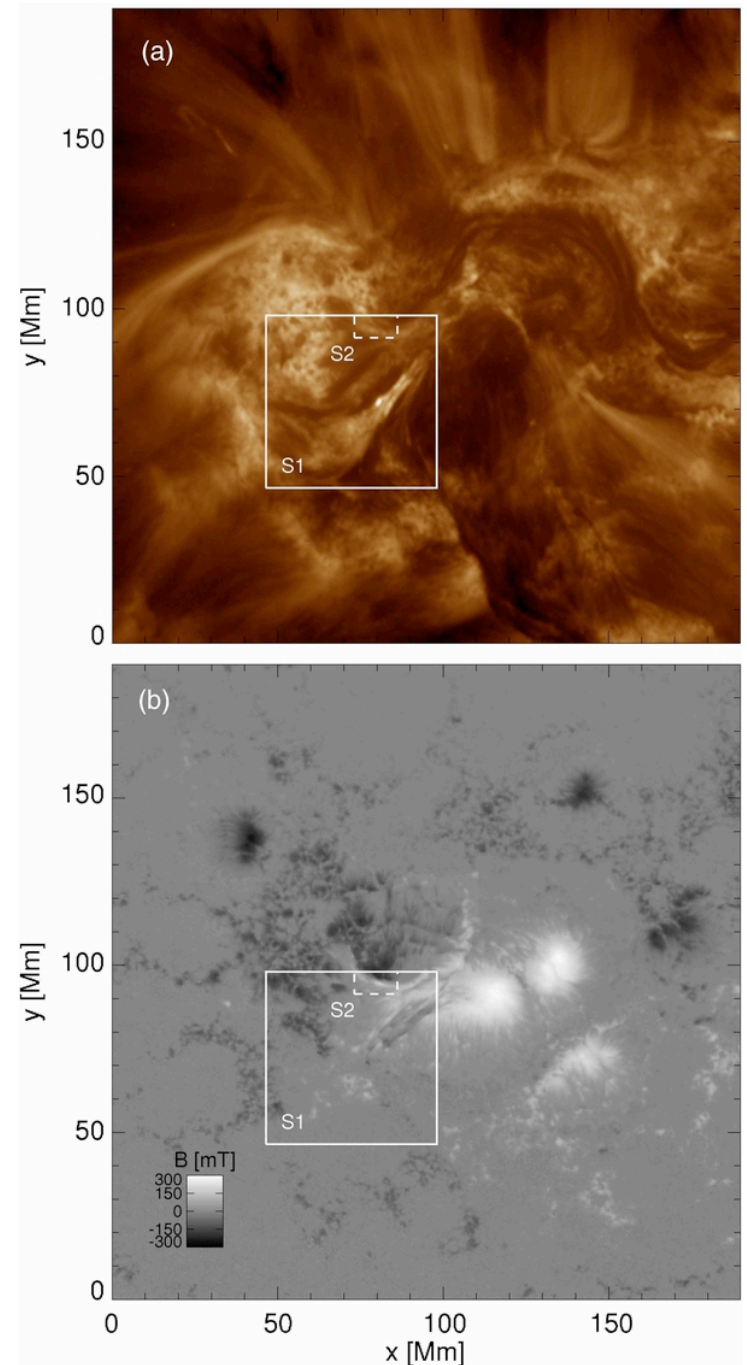
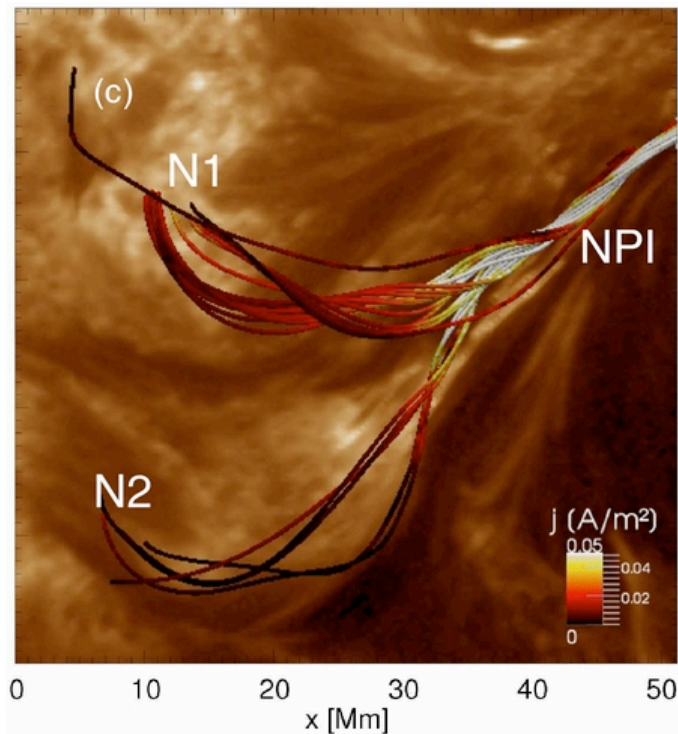


The Hi-C target was Active Region 11520  
July 11, 2012

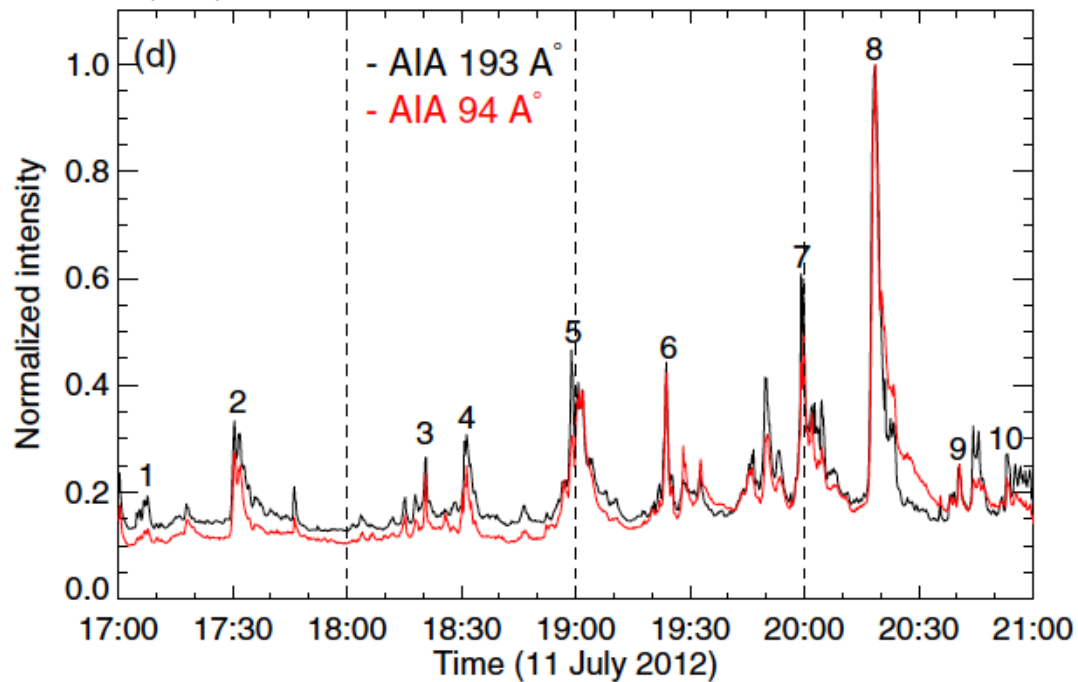
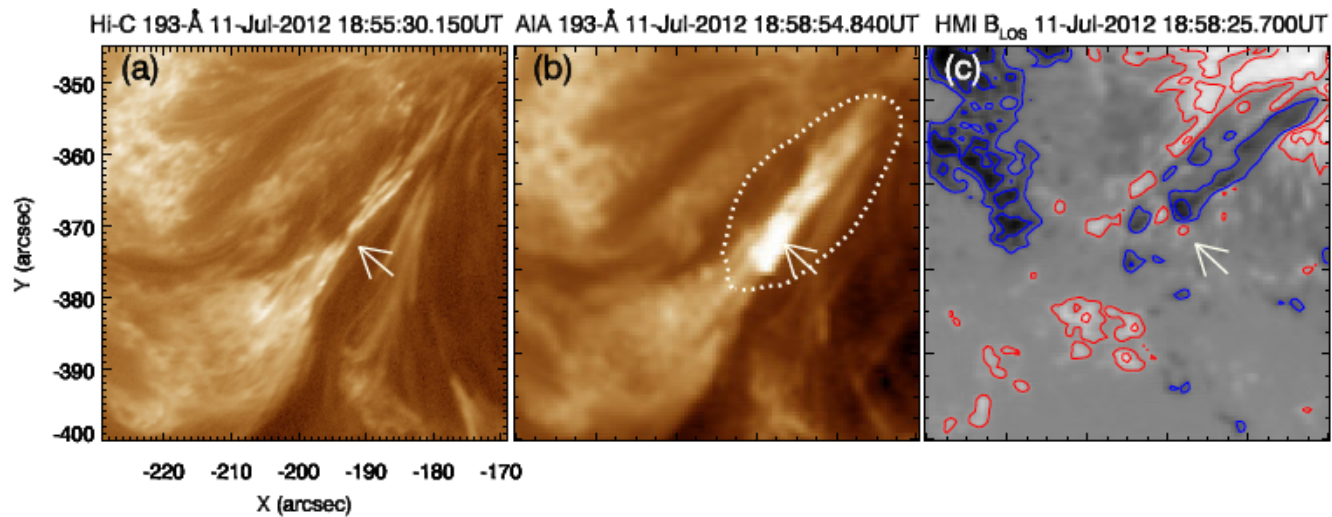
# Modeling the braided field

NLFFF extrapolation confirms the braided structure, and free magnetic energy estimates in the given volume

Thalmann, Tiwari & Wiegmann, 2014, ApJ

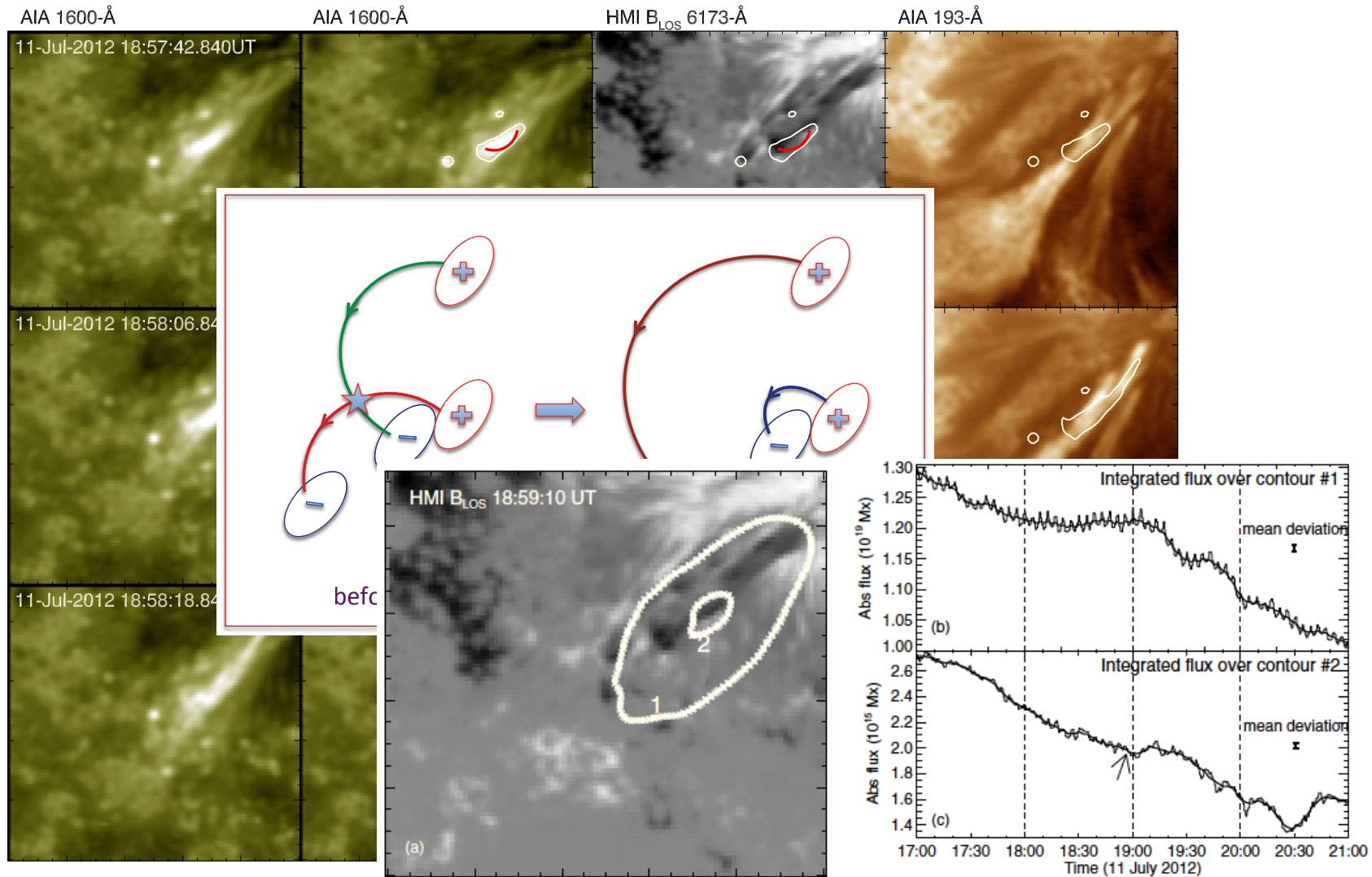


## External triggering of subflares...



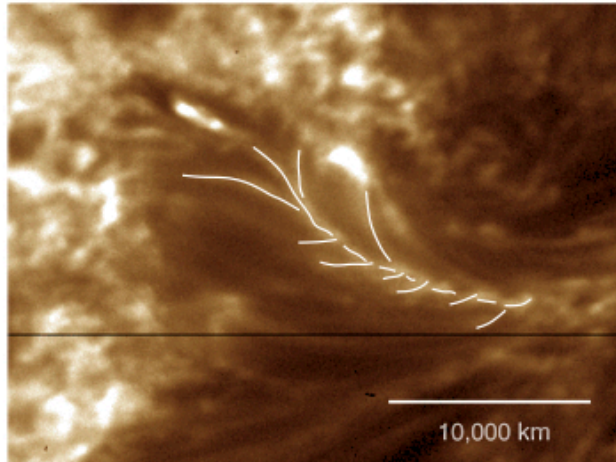


## External triggering of subflares...

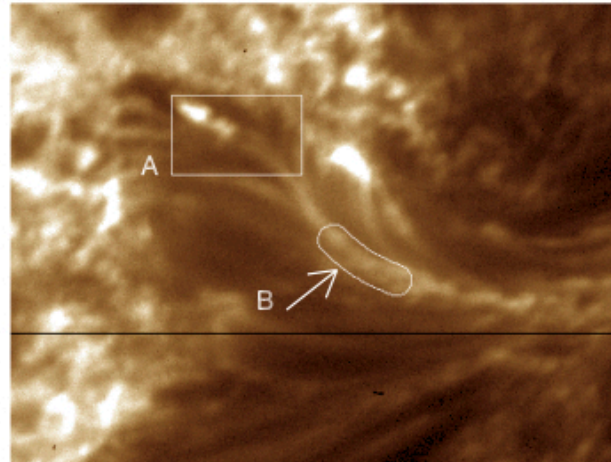


# High-resolution Coronal Imager (Hi-C)

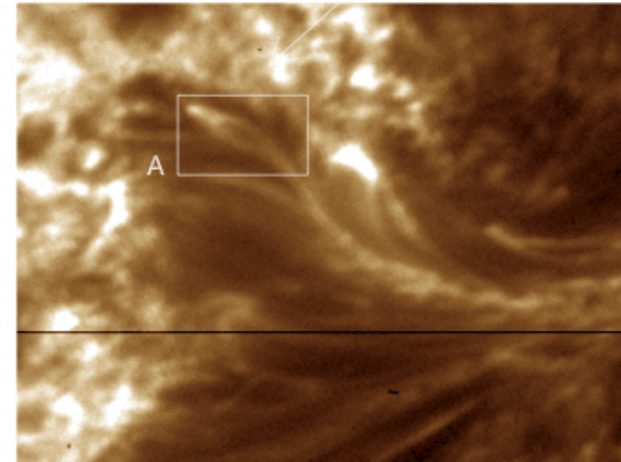
**a** Hi-C 193-Å: 18:53:28



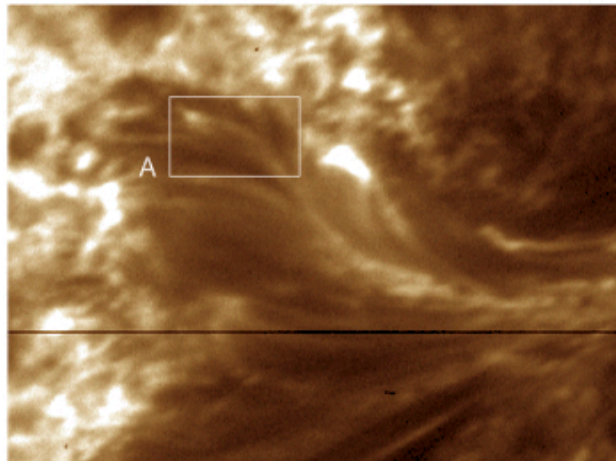
**b** Hi-C 193-Å: 18:53:45



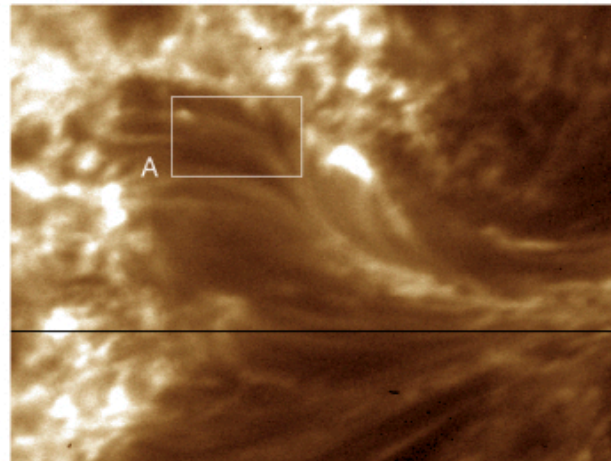
**c** Hi-C 193-Å: 18:54:13



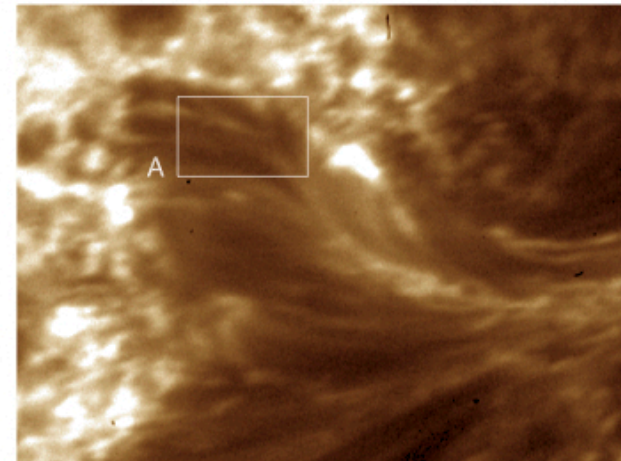
**d** Hi-C 193-Å: 18:54:41



**e** Hi-C 193-Å: 18:55:08

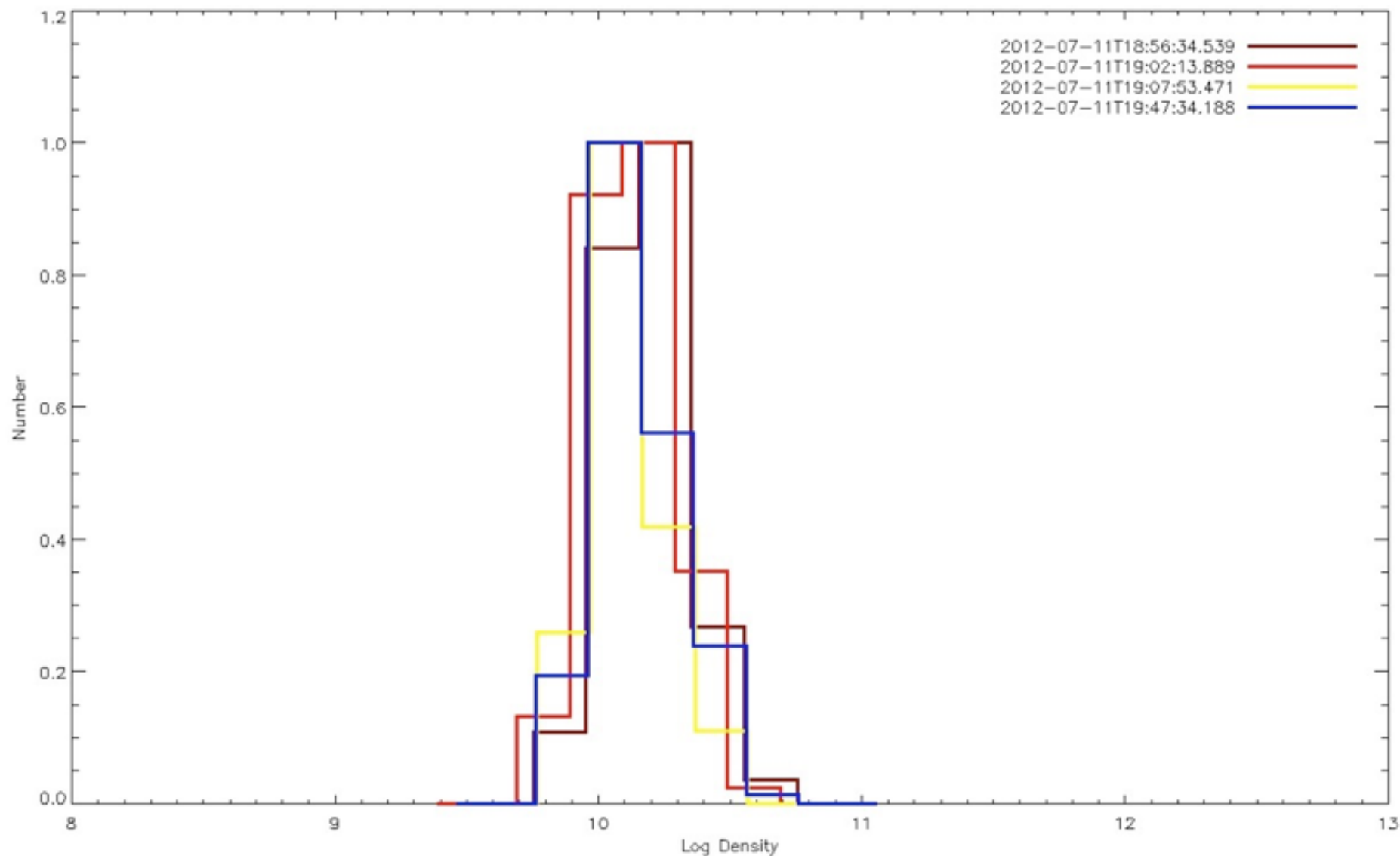


**f** Hi-C 193-Å: 18:55:36



Multiple strands join into this structure. It appears to unwind during Hi-C observations.  
*Cirtain et al, 2013, Nature*

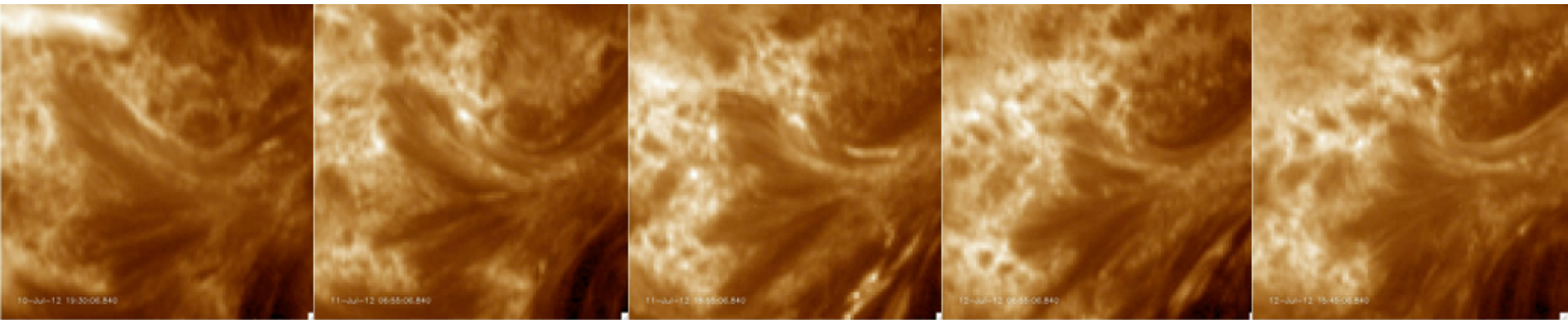
# High-resolution Coronal Imager (Hi-C)





# High-resolution Coronal Imager (Hi-C)

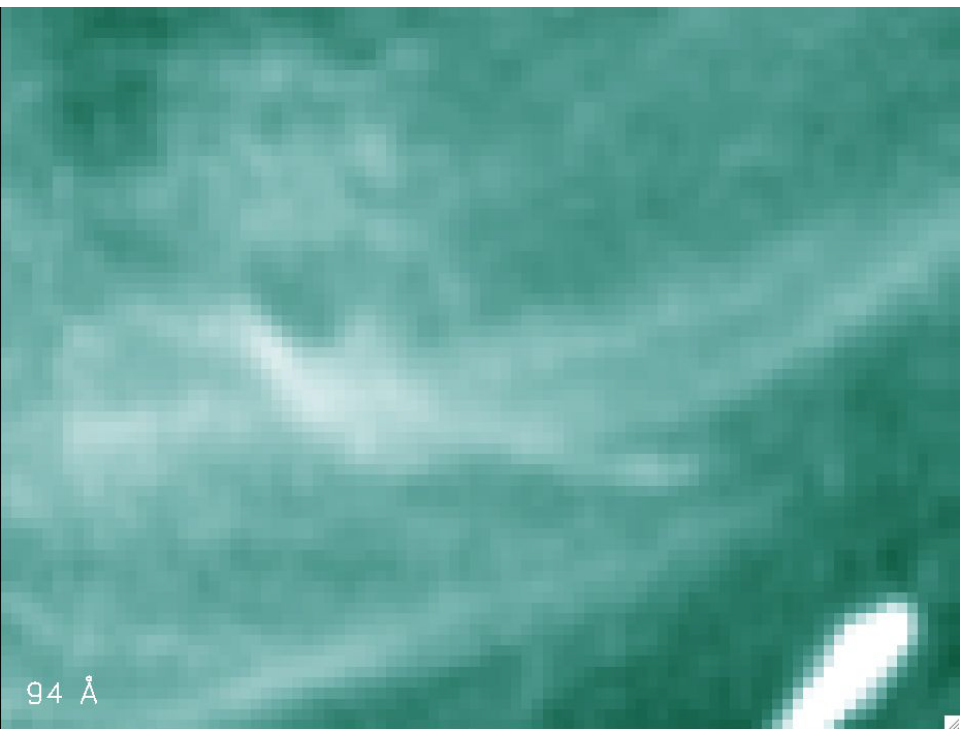
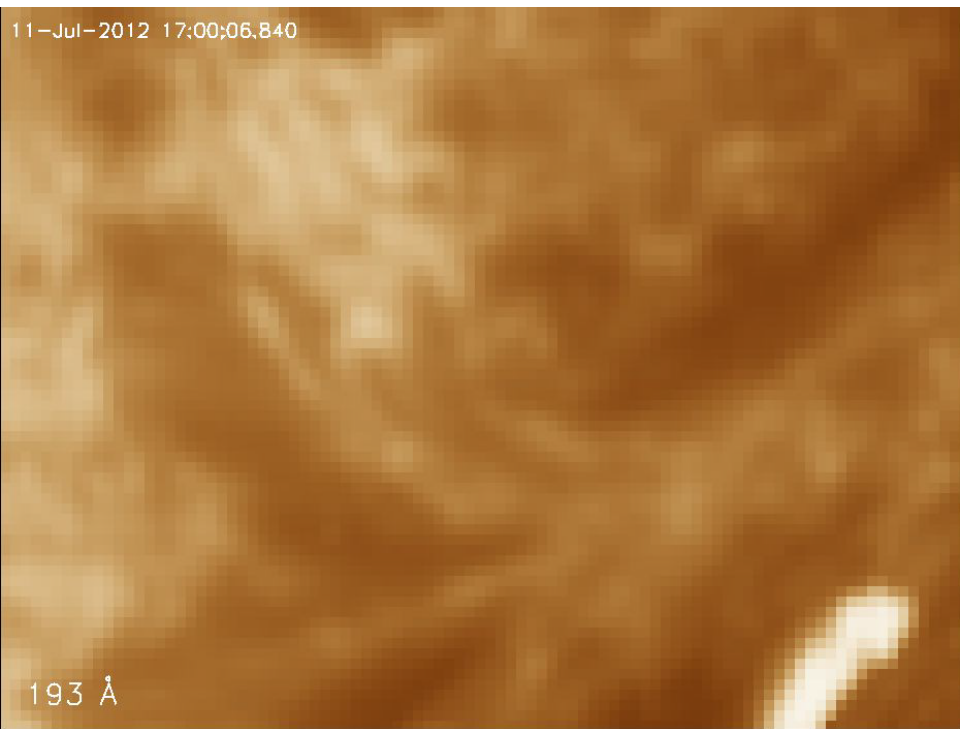
← - 1 day      Hi-C Flight Time      + 1 day →



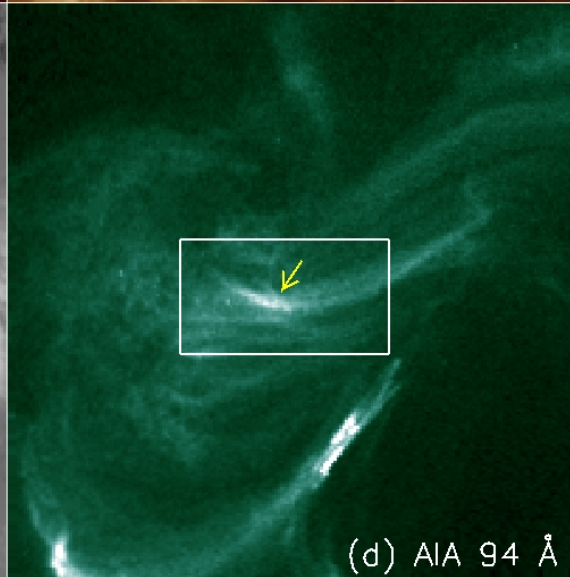
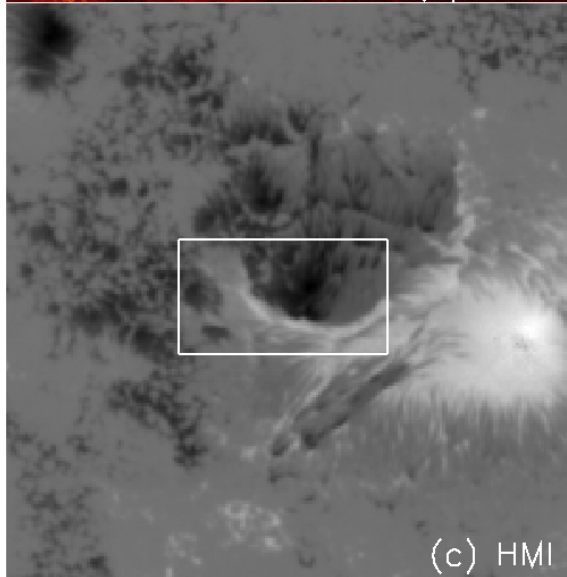
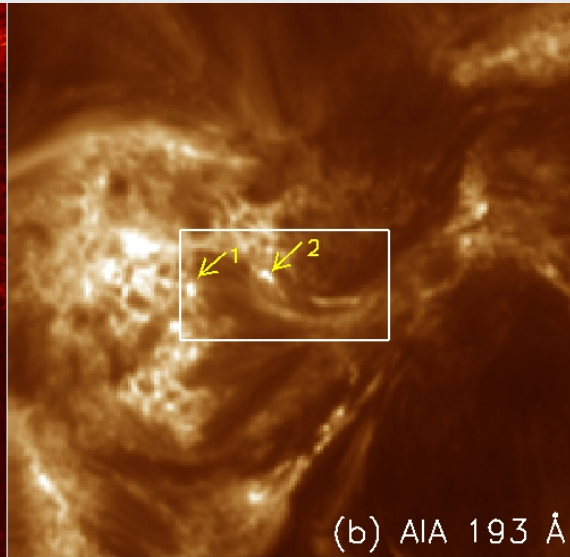
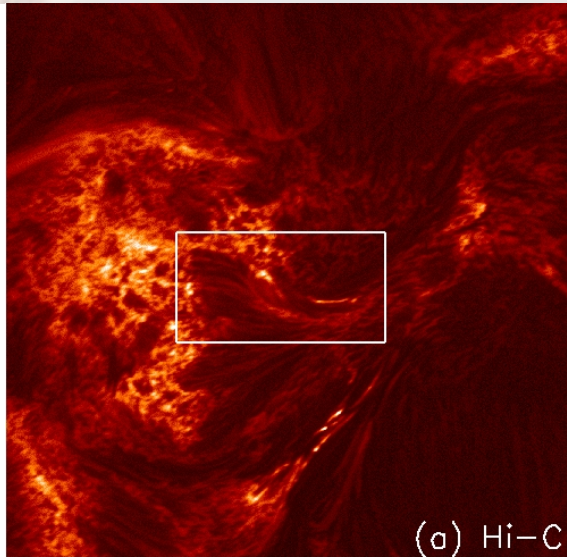
This is a long lived structure and is evident  $\pm$  24 hours from the Hi-C flight.

# High-resolution Coronal Imager (Hi-C)

11-Jul-2012 17:00:06.840



# High-resolution Coronal Imager (Hi-C)

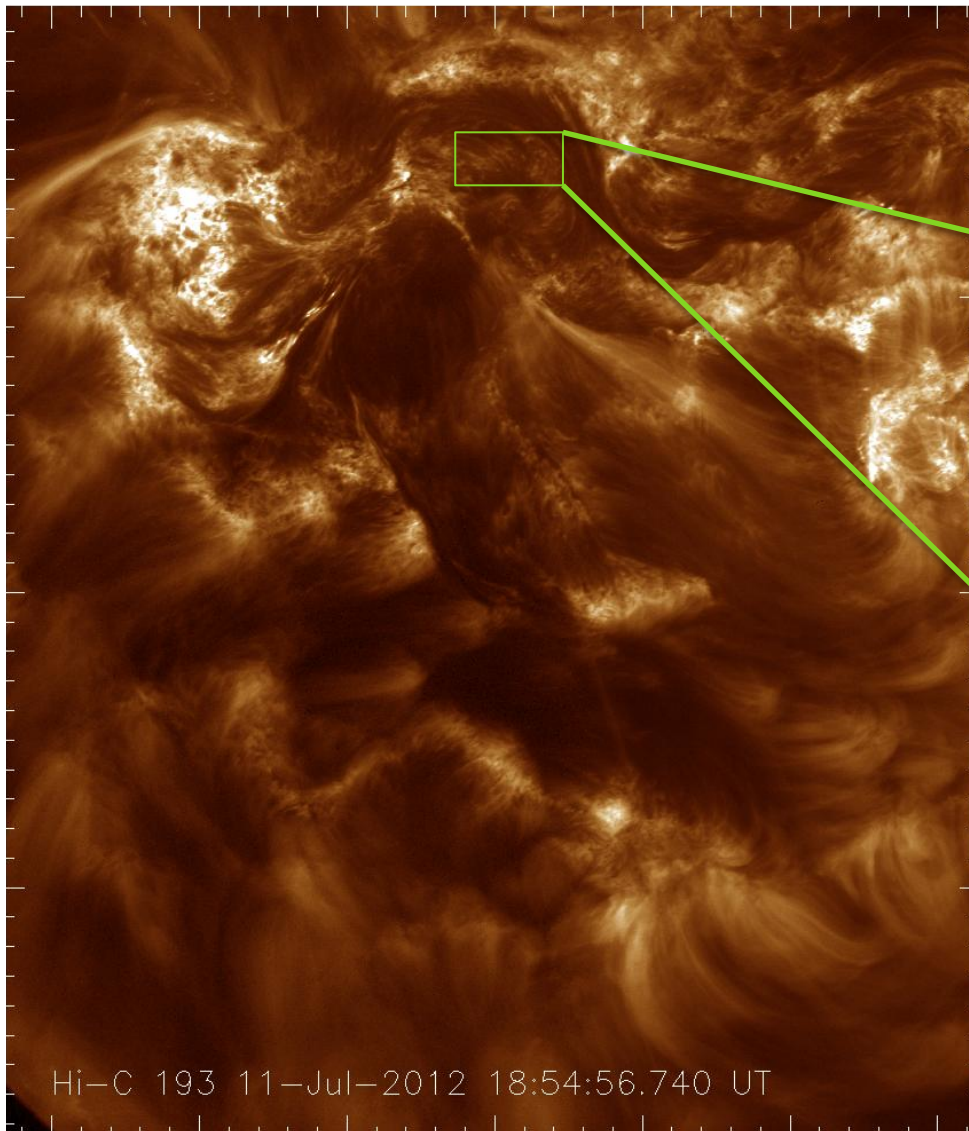


Brightenings in/near braided structure are associated with high temperature evolving loops.

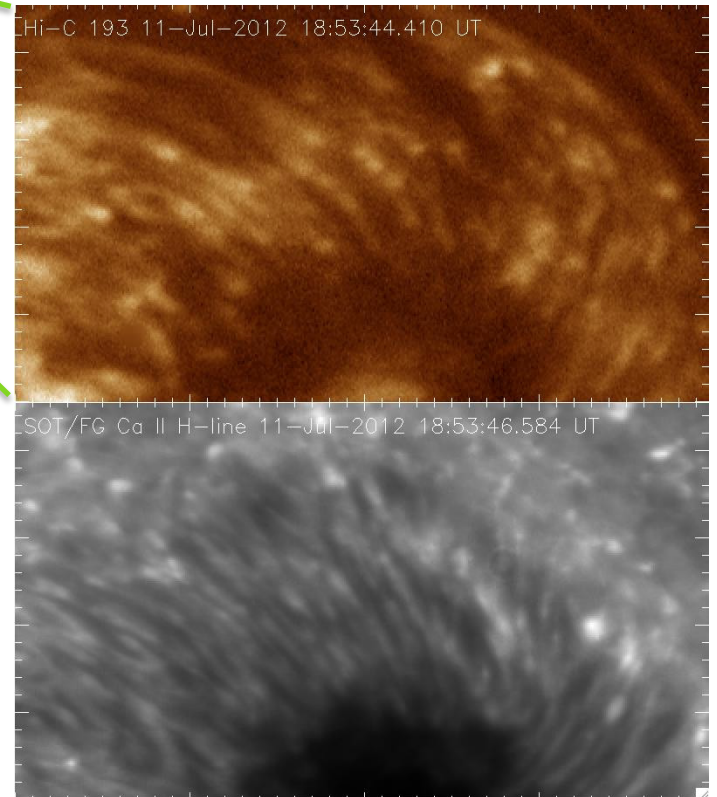


## Bright penumbral dots and penumbral microjets

Hi-C 193 Å



Penumbra; 18:53:44-18:55:30UT

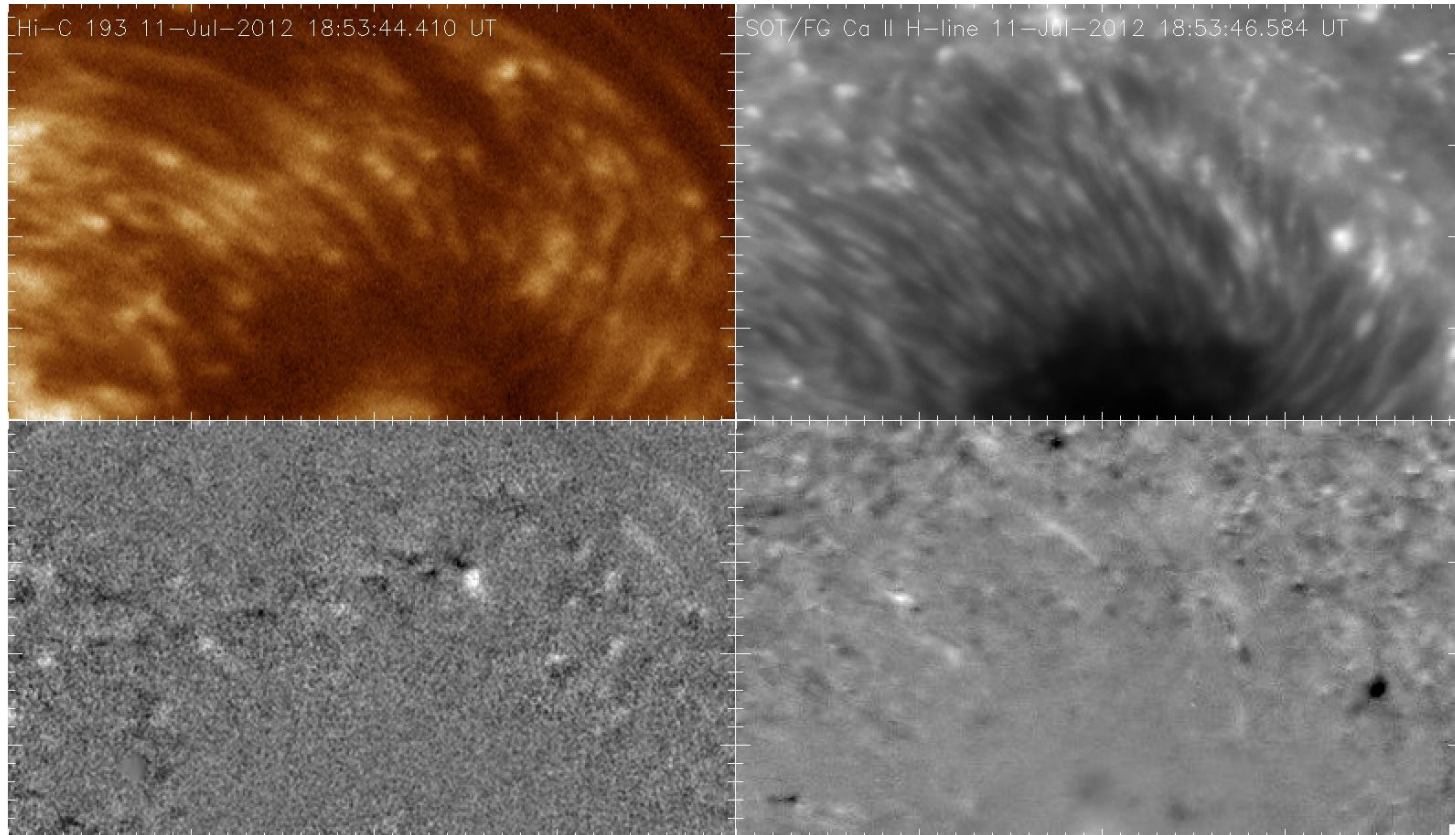


Hinode/SOT/FG Ca II H-line

# Bright penumbral dots and penumbral microjets

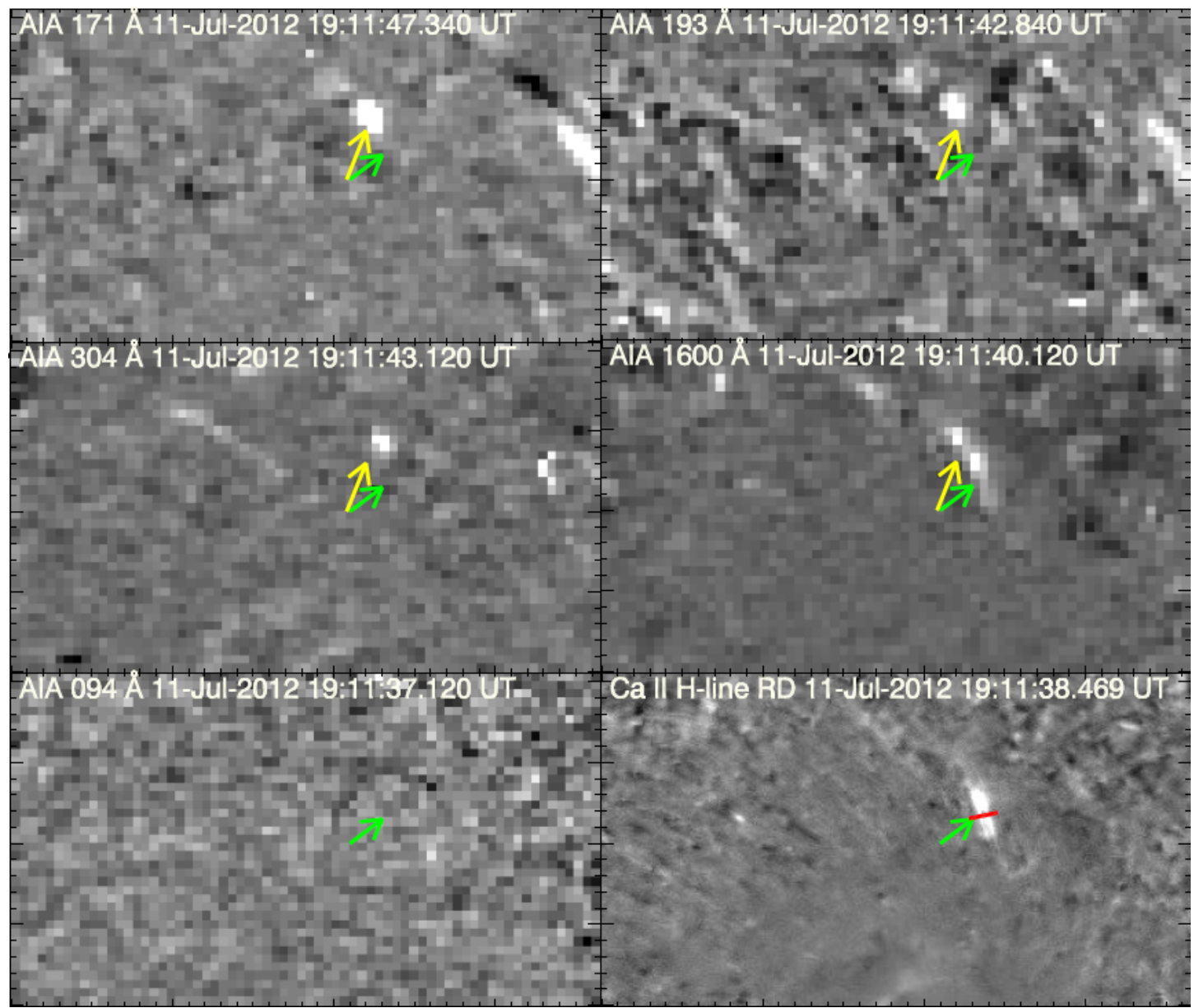
Hi-C 193 Å

SOT/FG Ca II H-line



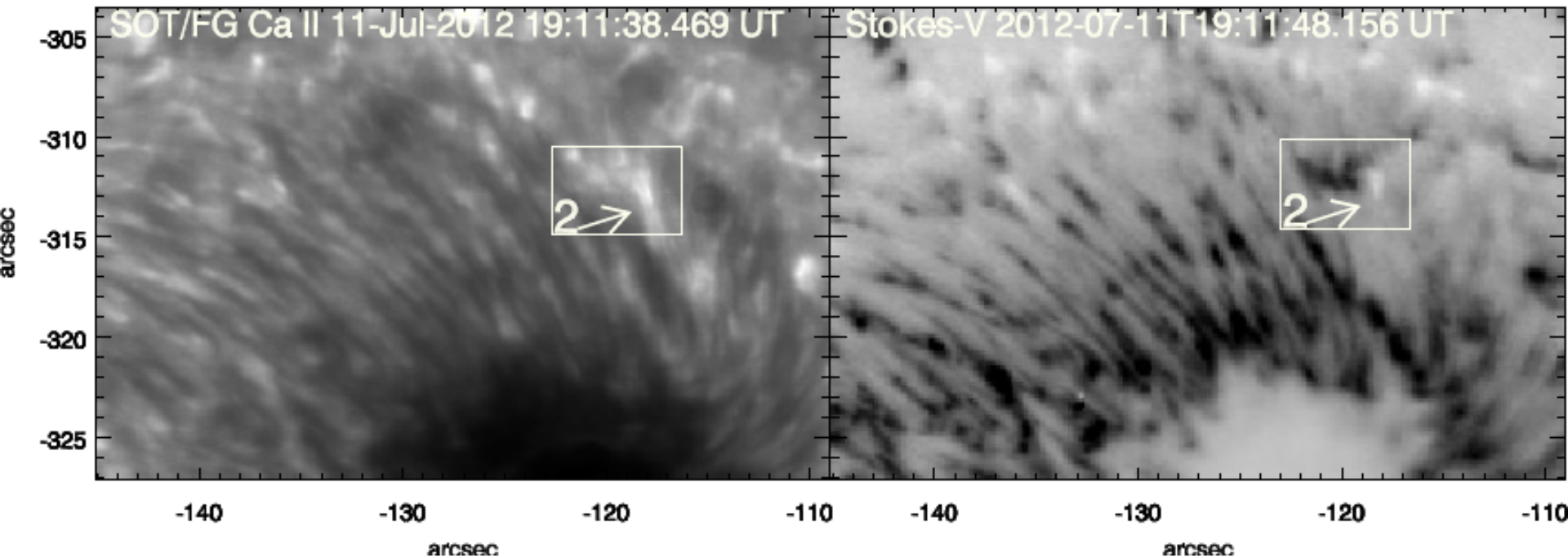
Lower frames are running differences

**Larger PJs:  
Coronal signatures**





## Mixed polarity at the feet of larger PJs:







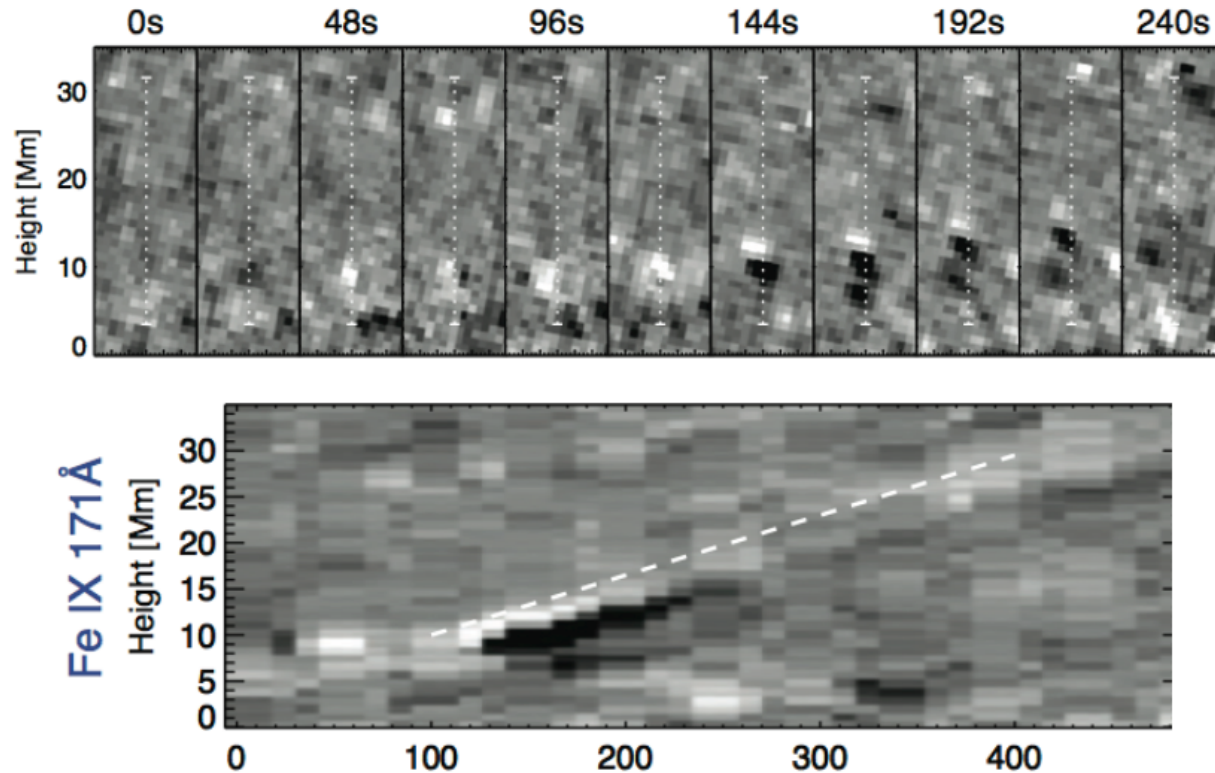
# Hi-C II – Exploring the Chromospheric-Coronal Connection

IRIS has shown many chromospheric and TR structures do not reach coronal heights.

But there must be a “classic” TR to coronal structures. And some dynamic chromospheric phenomenon may feed the corona.

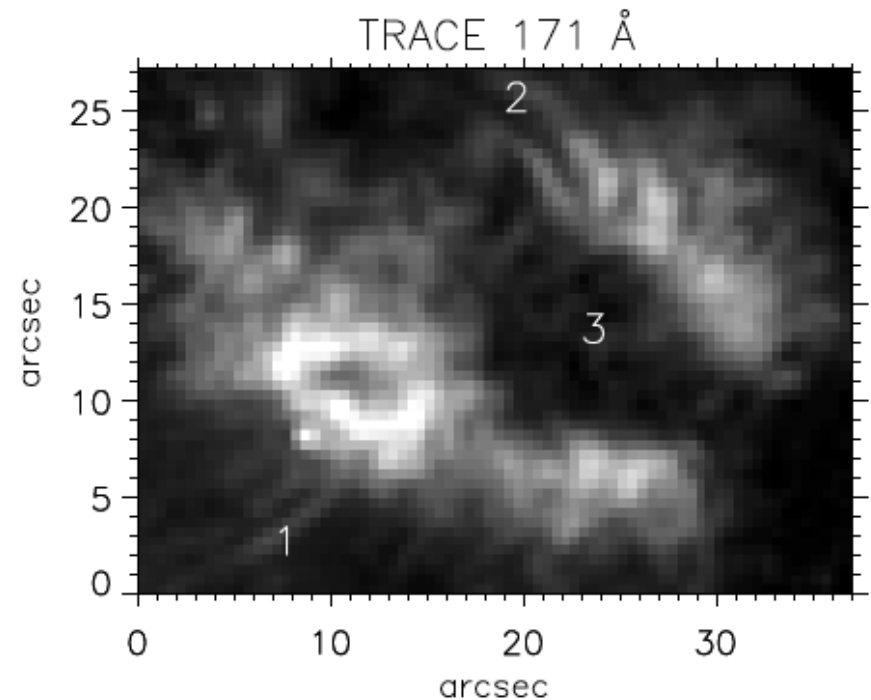
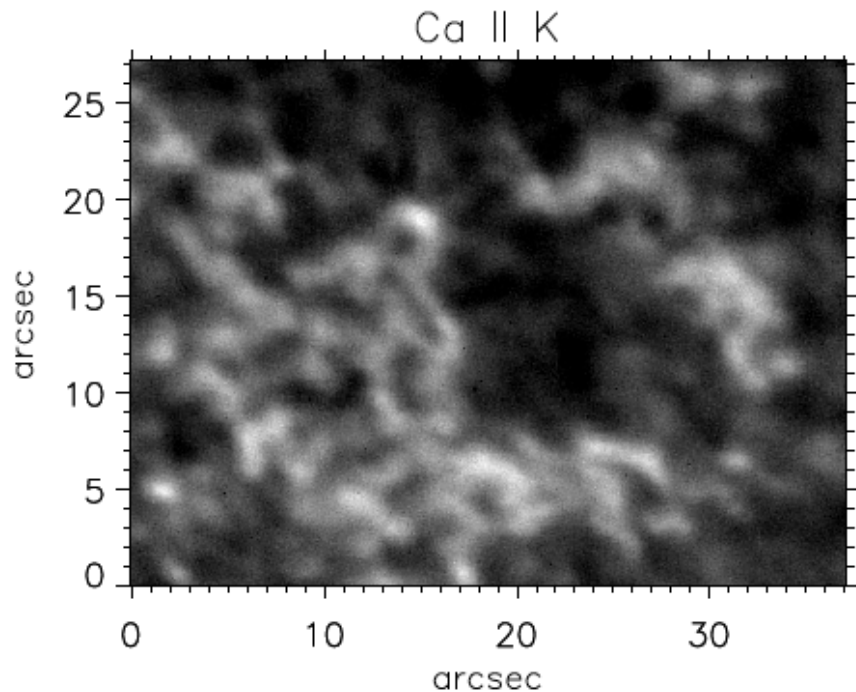
Hi-C II will look for the chromospheric-coronal connection in the two most obvious places, Type II spicules and hot core loops.

# Hi-C II – Exploring the Chromospheric-Coronal Connection



Do Type II spicules result in coronal plasma?

# Hi-C II – Exploring the Chromospheric-Coronal Connection



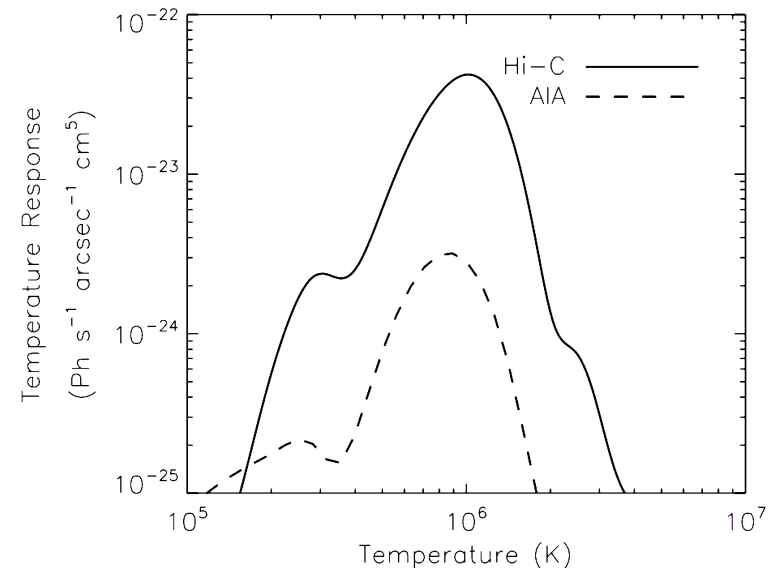
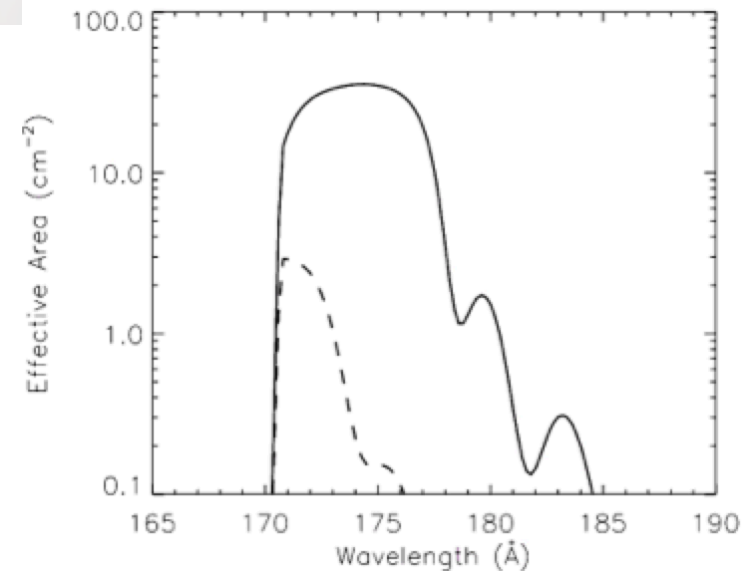
Can mass elements be traced through various TR temperatures?

De Pontieu et al, 2003



# Hi-C II

- Telescope design capable of  $\sim 0.25''$  resolution at the solar corona,
- Multi-layer coatings for EUV observations in the 171A passband,
- High sensitivity to EUV flux sufficient for a 5 s cadence,
- Pointing stability necessary to achieve resolution goal,
- Image readout and data storage capable of maintaining high-cadence observations, and
- Camera with low readout noise.
  - Camera for Flight #2 will feature an e2V 2Kx2K CCD with 12 $\mu$ m pixels
  - Using very similar board layout and electronics design as CLASP, HiC camera read noise expected not to exceed  $8\text{ e}^{-1}/\text{pixel}$



# Sounding Rocket Instruments at MSFC

